Formation fluid prediction through gas while drilling analysis

Relationship between mud gas data and downhole fluid samples

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Thesis to obtain the Master of Science Degree in

Petroleum Engineering

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February 2016

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“Anyone who has never made a mistake has never tried anything new.”

Albert Einstein

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Acknowledgments

Writing this acknowledgment concludes a long journey, which could never been possible without the support and encouragement of many people.

First of all, I would like to thank everyone associated with the Petroleum Engineering Master at Instituto Superior Técnico (IST) for the excellent work in the early stage of this new challenge. In special to Professor Leonardo Azevedo and Amilcar Soares for their enthusiasm and support, which motivate everyone to go further.

Secondly, I want to express my gratitude to Dr. Gionata Ferroni, Dr. António Costa e Silva and Dra. Maria João Pereira for their guidance and availability for the innumerous flash meetings. Only due to your collaboration and patience was possible to conclude this project.

I am also grateful to Geolog for making this research possible and for the technical support. I also want to leave a word of gratitude to all my Geolog colleagues, for their encouragement and suggestions for this research.

To Carlão, Gomes, Francela, Filipa, Caracol, Churro, and so many other friends that I had the luck to meet during these years at IST, I want to say thank you for all the good memories. It would not have been the same without you. A special thank you to Joana for every word since the beginning.

Last but not least, I would like to thank my mother, father, sister and brother for all your support during my course. Thank you for the all the encouragements and advices that made who I am today. Also, Tito and Thais, thank you for the support and interest in my progress.

Resumo

O fluido de reservatório é tipicamente obtido durante o período de testes do poço, através de ferramentas instaladas no interior deste ou à superfície. Assim, a composição do fluido é desconhecida até à chegada dos resultados das análises dos testes de PVT. Este estudo pretende servir-se dos dados de gás extraídos durante a perfuração para obter detalhes, quase em tempo real, sobre a composição do fluido de reservatório. Para tal, foram comparados dados de gás obtidos durante a perfuração com informações da composição do fluido de reservatório colectado durante os testes de poço. Após a análise dos resultados e do estudo de incerteza associado, foi criado um modelo com o intuito de antecipar, durante a perfuração, uma aproximação da composição do fluido de reservatório. O modelo obtido apresenta algumas limitações, uma vez que os dados disponíveis eram escassos e incompletos. Todavia o modelo alcançado demonstra fiabilidade na previsão da concentração de metano, etano, propano, n-butano e n-pentano. Para iso-butano e iso-pentano, presentes em menores concentrações, o modelo proposto apresenta um menor poder de previsão.

Palavras Chave

Mud logging; Análise de gás; Teste de poços; Avaliação da formação, Tempo real.

Abstract

Formation fluid is usually obtained during well tests, either by running downhole tools into the well or by collecting the fluid at surface. Therefore, its composition remains unknown until the arrival of the PVT well test results. This research intends to use mud gas information collected while drilling to obtain information about the reservoir fluid composition in near real time. To achieve this goal we compared mud gas data collected while drilling with reservoir fluid compositional studies. After the analysis of the results and the associated uncertainty evaluation, a model was created to forecast, while drilling, an approximation of reservoir fluid composition. The developed model has some limitations mainly due to the lack of sufficient and complete information. However, the model is able to predict in a robust way the molar concentration of methane, ethane, propane, n-butane and n-pentane. For iso-butane and iso-pentane, molecules present in low concentrations, the proposed model has lower predictability power.

Keywords

Mud logging; Gas analysis; Well tests; Formation evaluation, Real time.

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List of Acronyms

AGIP	Azienda Generale Italiana Petroli
Bh	Balance
BHS FG	Bottomhole flashed gas sample
BHS RG	Bottomhole recombined gas sample
BOP	Blowout Preventer
Ch	Character
CVD	Constant Volume Degasser
DST	Drill Stem Test
ECD	Equivalent Circulating Density
EEC	Extraction Efficiency Coefficient
FG	Flashed Gas
FID	Flame Ionization Detector
FP	Formation Pressure
GC	Gas Chromatograph
GDS	Gas Distribution System
GOC	Gas Oil Contact
GOR	Gas Oil Ratio
GQR	Gas Quality Ratio
MDT	Modular Formation Dynamics Tester
Pb	Bubble Point Pressure
PPM	Parts Per Million
PVT	Pressure Volume and Temperature
Pwf	Wellbore Flowing Pressure
OBM	Oil Based Mud
OWC	Oil Water Contact
QGM	Quantitative Gas Measurement
RG	Recombined Gas
ROP	Rate of Penetration
TBP	Total Bottomhole Pressure
WBM	Water Based Mud
Wh	Wetness

1

Introduction

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1.1. Nature and scope of this project

The current thesis reports the main results of the work carried out as an employee at *Geolog*, Milan, Italy, under the supervision of Mr. Gionata Ferroni, *Geolog* Formation Evaluation Services Manager, and co-supervised by Professor Maria João Pereira from Instituto Superior Técnico.

This research was carried out in the scope of the Dissertation/Final Project course from the final year of the Master in Petroleum Engineering, from Civil Engineering Department of Instituto Superior Técnico, Lisbon, Portugal.

1.2. Thesis structure

The present thesis is divided into six main parts. The first chapter introduces the scope and objectives of this thesis, gives a small reference about *Geolog*, and presents an overview about drilling operations and mud logging service.

In the second chapter the formation evaluation topic is briefly introduced, highlighting the importance of using mud gas services. The details about the datasets and methodology are revealed. Surface gas and downhole fluid collection methods are also presented.

Chapter three pinpoints the data collection techniques for each well and presents the quality control test performed for each dataset. The applied approach aims to ensure the reliability of surface and subsurface information.

Chapter four tackles the data analysis and processing, as well as, the uncertainty research between the relationships studied. Both datasets, downhole fluid and surface gas data, were transformed in order to become comparable.

The fifth chapter reports the studies behind the development of the predictive model. The details about the regression of the data are revealed, as well as, the uncertainty evaluation of the model.

The final chapter consists on the presentation and discussion of the results obtained, and the main conclusions that can be drawn from this work, followed by a brief suggestion for future work.

1.3. Geolog

Geolog SpA was founded in 1982, in Italy, to provide mud logging services to *Azienda Generale Italiana Petroli* (AGIP) on geothermal, oil and gas wells. From its early years, *Geolog* 's strong technological culture led to the development of a number of innovative solutions and highly technological patents in the mud logging arena.

The Italian crisis of 1994, during which the company moved abroad, opening bases in Tunisia, Congo and Venezuela, servicing AGIP's international operations, acted as a catalyst for the company's international expansion. Current management acquired the company in 2001 and has been able to develop innovative solutions and technological patents into commercial products and services, thereby significantly growing the customer base, not only to International Oil Companies but also to National Oil Companies worldwide.

Geolog 's mud logging services are centered on the optimization of the overall drilling times and costs of each well and the acquisition of quality data to improve formation evaluation. Following the recent mergers and acquisitions in the mud logging sector, Geolog is now the largest independent international mud logging company in the world. Therefore, presents itself as the only solution to clients seeking for an independent mud logging service provider.

Geolog is presently involved in exploration, development, deep offshore and high-pressure high-temperature wells. *Geolog* ´s growth is attributed, amongst others, to its technological leadership and its strong focus on proprietary research and development. As such, *Geolog* invests heavily in R&D with a target to produce a new patent, on average, every two years.

Geolog ´s products and services are based on 3 key industry requirements, as showed in figure 1. *Geolog* strongly believes in this approach and the results are clearly visible with the fast growth of the company's global performances.

Figure 1 – *Geolog* statements, courtesy of Geolog.

1.4. Study objectives

The scope of this project is to study the relationship between the composition of mud gas obtained by the mud logging companies, in real-time while drilling, and the downhole fluid samples collected during well tests and then analyzed in the laboratories.

The goal is to recognize consistent relationships, and measure the data uncertainty in the comparisons between mud gas and bottomhole fluid data. The purpose of this study is the desire to build an inverse model able to predict, in near real time while drilling, an approximation of the real reservoir fluid composition.

This is an important topic because in the case of borehole instability or any other hostile circumstances that prevent the realization of wireline logging, mud gas analysis may be the only formation evaluation tool available to provide hydrocarbon type information.

It is also relevant to stress the advantage of mud gas analysis in the decision for the testing tool string design, in the depth selection for the sampling points, and can also help focusing the formation evaluation program on any spotted anomaly.

1.5. Drilling operation overview

Drilling is one of the most important stages in the oil production industry. Drilling consists in entering physically the reservoir, which enables the acquisition of valuable information about the nature of the rock and the fluids contained in it.

Nowadays almost all wells are drilled with rotary drilling rigs, like the one presented in the figure 2. The hole, called wellbore, is created by the bit that is at the end of a long length of steel pipe, which is rotated by the rotary system. The rotary rig consists of four major systems: power, hoisting, rotary, and circulation systems.

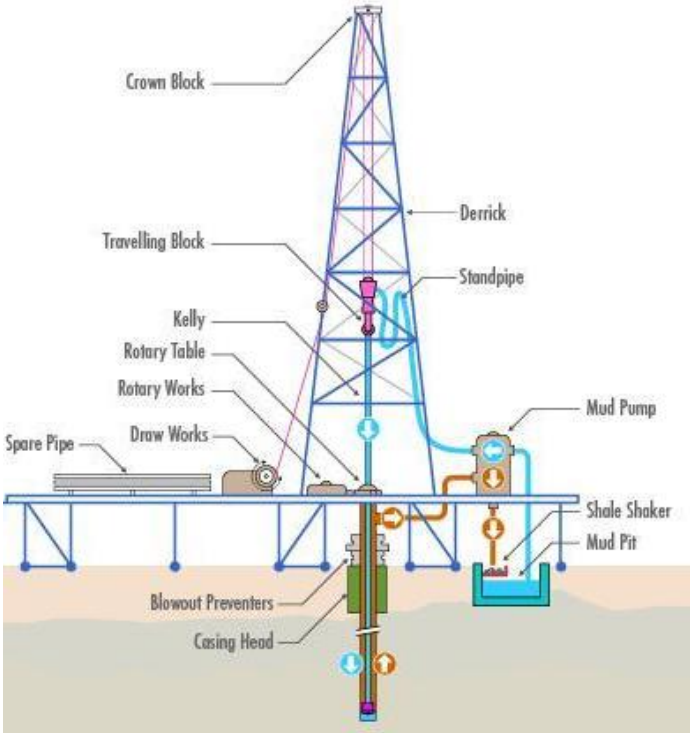

Figure 2 –Rotary drilling rig. [17]

1.5.1. Power system

The power system supplies energy for all the other systems in the rig, as well as, for the rig lights and other motors. The major movers are diesel engines, which are often located on the ground in the back of the rig and are the source of rig power.

The number of engines in the rig depends on the rig size, drilling depth, et cetera. An array of belts, pulleys, shafts, gears and chains, called compounder, is used to transmit mechanically the power from the diesel engines to the rig. Newer rigs are diesel-electrical rigs with the diesel engines coupled to an alternating current or direct current generator that supplies electrical power through an electrical cable to the rig. [19]

1.5.2. Hoisting system

The hoisting system is used to raise, lower and suspend equipment in the well, as shown in figure 3. The derrick or mast is the steel tower above the well that supports the crown block at the top and provides support for the drillpipes to be stacked vertically as they are pulled from the well.

The hoisting line is spooled around a reel on a horizontal shaft in a steel frame called drawworks on the drill floor. The prime movers drive the drawworks to wind and unwind the drilling line. The driller controls the drawworks from a brake on the rig floor.

On the drilling rig, there are two sets of wheels (sheaves) on horizontal shafts in steel frames called blocks. The drilling line from the drawworks goes over a sheave in the crown block that is fixed at the top of the derrick or mast. It then goes down to and around a sheave in the traveling block that is suspended in the derrick or mast. The drilling line goes back and forth through sheaves in the crown and traveling block 4 to 12 times. The end of the drilling line is fixed to a deadline anchor located under the drill floor. [19]

Below the traveling block there is a hook for attaching equipment. As the drilling line is reeled in or out of the drawworks, the traveling block and hook rises and falls in the derrick to raise and lower equipment inside the well.

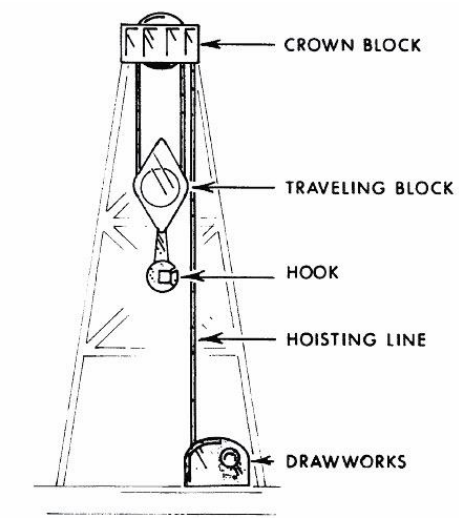

Figure 3 – Hoisting system. [19]

1.5.3. Rotating system

The hole is cut using the rotating system, as illustrated in figure 4. The stack of drillpipes, bit, and related attachments are often denominated by drillstring. Suspended from the hook directly below the traveling block is the swivel. The swivel allows the drillstring that is attached below it to rotate on bearings in the swivel while the weight of the pipe is suspended from the derrick or mast.

Below the swivel is located a very strong steel pipe called the kelly. The kelly has sides to enable it to be gripped and turned by the rotary table. The kelly turns all the pipe below it to drill the hole. The rotary table is a circular table in the drill floor that is turned clockwise by the prime movers. The kelly goes through a fitting called the kelly bushing, which fits onto the master bushing on the rotary table. Rollers in the kelly bushing allow the kelly to slide down through the kelly bushing as the well is drilled deeper. [19]

At newer drilling rigs the drillstring is rotated by a top drive or power swivel. It is a large electrical or hydraulic motor that generates more than 1,000 horsepower. The top drive or power swivel is hung from the hook on the traveling block or is an integral part of the derrick or mast and turns a shaft into which the drillstring is screwed. It moves up and down the derrick or mast while drilling. A top drive system enables a faster and safer drilling activity than with a rotary table method. An example of the previous statement is while

making a connection: a top drive system allows adding three joints of drillpipes to the drillstring at a time instead of one to save rig time. [19]

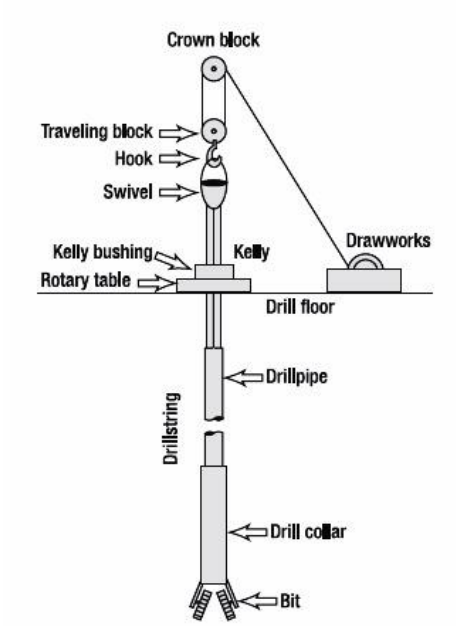

Figure 4 – Kelly rotating system. [19]

1.5.4. Circulating system

The circulating system pumps drilling fluid in and back out of the wellbore. Several steel tanks on the ground are used to store the drilling mud. Usually these tanks have rotating paddles on a shaft, called mud agitators, in order to mix the drilling fluid ensuring its homogeneous properties. The prime movers drive large pumps, which use pistons in cylinders to pump the drilling mud from the mud tank to the well.

Drilling mud can be a mixture of special clay with water (water-based drilling mud), oil (oil-based drilling mud), a mixture of oil and water (emulsion mud), or a synthetic organic matter and water mixture (synthetic-based drilling mud).

The mud flows from the pumps through a long rubber tube, the mud hose, and into the swivel. The drilling mud then flows down through the rotating drillstring and jets out through the holes in the drilling bit on the bottom of the well. The drilling mud picks the rock chips (cuttings) off the bottom of the well and flows up the well in the space between the rotating drillstring and well walls (annulus). At the top of the well, the mud flows through the blowout preventer (BOP) to the mud return line and finally to a series of vibrating screens called the shale shakers. The shale shakers are designed to separate the coarser well cuttings from the drilling mud.

If necessary the mud then flows through other solids control equipment such as de-sanders and de-silters where the mud is centrifuged to remove finer particles. In the final stage the mud flows back into the mud tanks to be re-circulated into the well.

Drilling mud is necessary in drilling operations for several purposes. One of them is to remove cuttings from the bottom of the well in order to have a good hole cleaning. When mud flows across the bit, it cools, lubricates and cleans the cuttings from the teeth of the bit. In very soft sediments, the jetting action of the drilling mud squirting out of the bit also helps to drill the well.

The most important purpose of the drilling mud is to control the formation pressure in order to prevent blowouts. At the bottom of the well there are two fluid pressures on two different fluids. Pressure on fluids within the pores of the rock (reservoir or fluid pressure) tries to force the fluids to flow through the rock into the well, as represented in figure 5. The weight of the mud column filling the well applies a pressure that tries to balance the formation fluid pressure. Regarding the mentioned pressures there are two possible conditions: overbalance or underbalance. If the pressure of the fluid on the subsurface rock is greater than the pressure of the drilling fluid (underbalance condition), formation fluids will flow out of the rock into the well. This situation can trigger a blowout where fluids flow uncontrolled and often violently onto the surface.

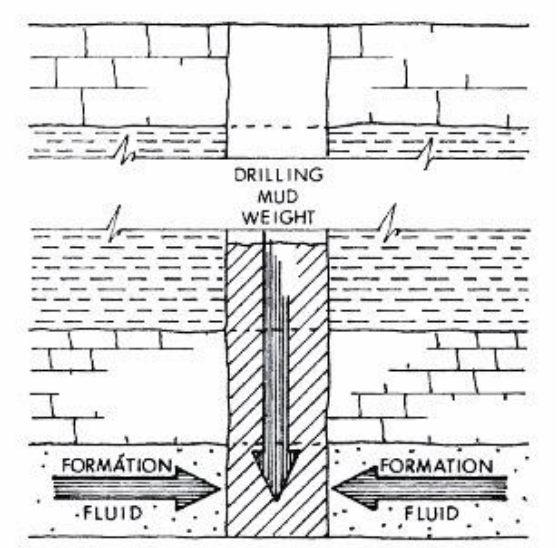

Figure 5 – Pressures on the bottom of the well. [20]

In order to control formation fluid pressure, the weight of the drilling fluid is adjusted to exert a greater pressure on the bottom of the well than the expected pore pressure (overbalance condition). Depending on the overbalance severity some drilling fluid is then forced into the surrounding rocks. The rocks act as a filter, therefore the solid mud particles cover the sides of the well forming a filtrate (mud cake) as the fluids penetrates the nearby formations. This filtrate is important once it stabilizes the sides of the well and prevents subsurface fluids from flowing into the well.

1.5.5. Well monitoring

After drilling activity begins, the manpower required to drill the well and solve any drilling problems that can occur are provided by the drilling contractor, the well operator, various drilling services companies, and special consultants. Final authority rests either on the drilling contractor when the rig is drilling on a cost-

per-foot basis, or on the oil company representative when the rig is drilling on a cost-per-day basis. [20] Figure 6 shows a typical drilling organization used by the drilling contractor and well operator when a well is drilled on a cost-per-day-basis.

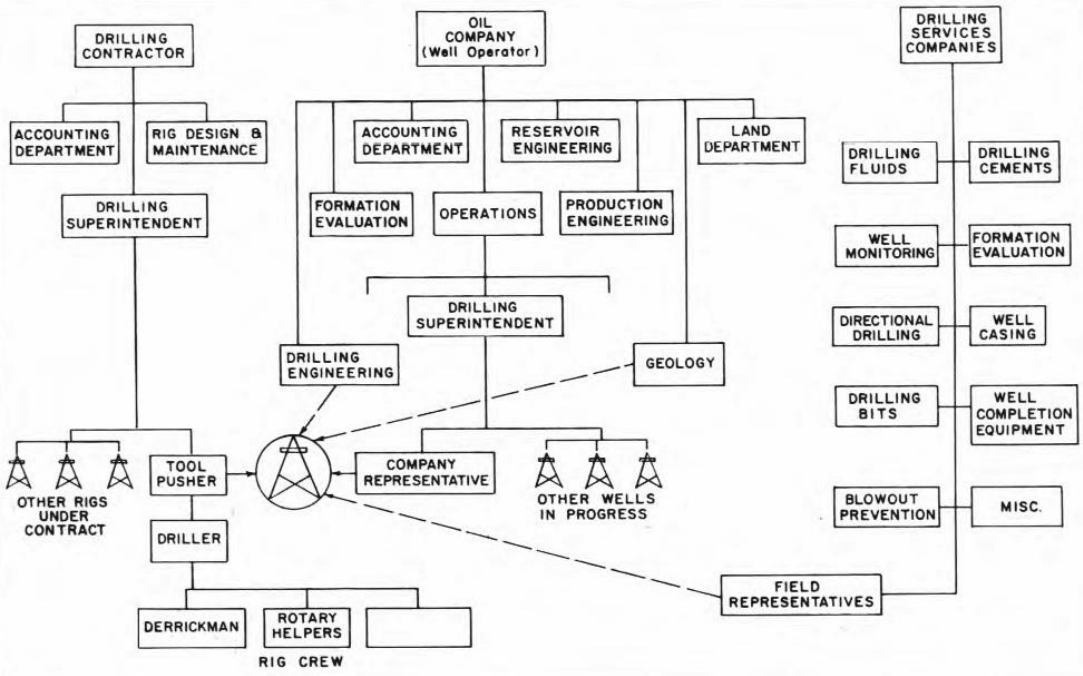

Figure 6 –Typical drilling rig organization for a cost per-day basis. [20]

Safety and efficient decisions require constant monitoring of the well to quickly detect drilling problems. To monitor the well there are devices recording and displaying parameters such as depth, penetration rate, hook load, rotary speed, rotary torque, pump rate, pump pressure, mud density, mud temperature, gas content in the mud, hazard gas content in the air, pit level and mud flow rate.

In some wells a centralized monitoring system is used, this service is called mud logging or surface logging. The mud logging unit provides detailed information about the formation being drilled, the fluids brought to the surface within the mud, and also a record of all the drilling parameters.

1.5.6. Mud logging service

Mud logging is a contract service, which the oil company employs to monitor wellsite activities, and to analyze the cuttings for lithology identification and hydrocarbon shows. The resulting plots of those wellsite activities and cuttings analysis versus depth is designated as mud log.

The quality control of those operations is the responsibility of the wellsite geologist. The wellsite geologist must be certain that the equipment necessary to monitor wellsite activities is working properly, and is used to its best advantage. Depending on the situation, the mud logging unit may be a simple standard unit (monitoring gas, ROP and pump strokes only), or a more sophisticated computerized unit monitoring a large range of drilling and tripping parameters around the rig.

There are several broad objectives targeted by mud logging: identify potentially productive hydrocarbon-bearing formations, identify markers or correlated geological formations, and provide data to the driller that enables safe and economically optimized operations. The actions performed to accomplish these objectives include the following: [20]

- Collecting drill cuttings;
- Describing the cuttings;
- Interpreting the described cuttings (lithology);
- Estimating properties such as porosity and permeability of the drilled formation;
- Maintaining and monitoring drilling-related and safety-related equipment;
- Estimating the pore pressure of the drilled formation;
- Collecting, monitoring, and evaluating hydrocarbons released from the drilled formations;
- Assessing the producibility of hydrocarbon-bearing formations;
- Maintaining a record of drilling parameters.

As mentioned earlier, the range of services provided by the mud logging company can vary, generally the more "unknown" the area to be drilled, the more advanced the service. However there are certain aspects of mud logging that are standard to all the jobs, such as:

- Mud-gas separation methods: All mud logging operations use some sort of "gas trap" to release hydrocarbons from the drilling fluid. The extracted gases are then transported, via some type of tubing, to the logging unit for analysis;
- Pit level recorders: These sensors are critical for early prevention of well problems (kicks, lost circulation) and they must be operatives at all times;
- Depth recorder - This sensor will vary with the mud logging company. Regardless of the system, the depth at any time should always be known. An agreement between the driller's depth, mud loggers depth and wireline depth is difficult to reach, but any large discrepancy should be noted and the cause of the discrepancy determined.

There are several indicators, as showed in figure 7, that enable the mud loggers to understand the dynamic conditions of the well and to have a quick reaction in case of dangerous conditions.

- Mud pit level – the circulation system works like a closed system, the mud is pumped through the drill string coming out through the bit nozzles, then moves up in the annulus to return to the pit room. Therefore any rapid increase in this system can mean an influx from the bottom of the well, in the other hand a decrease in volume can indicate downhole or surface losses.
- Mud chloride content – if there is a significant change in the ions present in the drilling fluid that can indicate an influx of formation water, indicating an underbalance condition in the well.
- Lithology and mineralogy – the lithological analysis can give information about over pressurized areas, where the pore pressure changes drastically which can cause a fluid influx to the well. If this conclusion is predicted soon enough the driller can adjust the mud weight to face the expected problems.

- Monitoring the rate of cuttings return – Once the circulation system is theoretically closed, the amount of cuttings produced at the bottom of the hole should reach the surface at a regular rate depending on the penetration rate. If this does not happen probably hole-cleaning problem will be faced.
- Total gas – The gas concentration in the drilling fluid can be an indicator of well pressure balance. The ideal situation is to have a mud weight superior to pore pressure gradient. If this is not possible the second safest option is to have an equivalent circulating density (ECD) bigger than pore pressure gradient. In this case, because the hydrostatic mud pressure is smaller than pore pressure, each time the pumps are off an influx of formation fluid will occur.

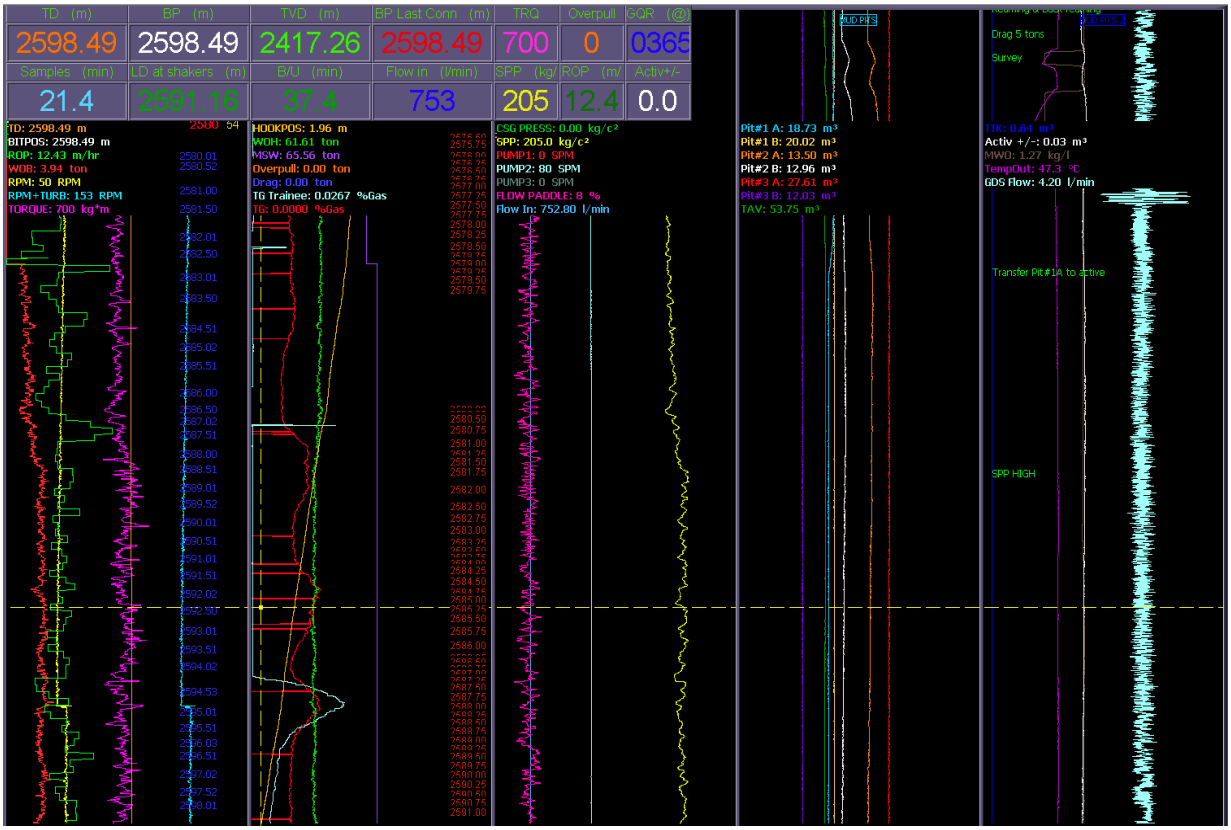

Figure 7 – Real time monitoring, courtesy of Geolog.

2

Theoretical Framework

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2.1. History of formation evaluation

Identifying compartmentalization, quantifying connectivity, and assessing the presence of compositional grading are critically important to reservoir management, particularly in deepwater projects where uncertainties are large and mistakes are costly. Individually, geochemistry, downhole fluid, and mud gas analyses have provided valuable insights into reservoir studies, but each analytical method relies on different fluid behaviors and has different implications. When these analytic methods are systematically combined and consistently applied, the synergy delivers a much more accurate and robust picture of the reservoir. [14]

The ability of mud-gas logs to delineate different hydrocarbon types is a function of drilling and mud parameters as well as the technology used in the extraction and analysis of the mud gases. Historically, odor, the presence and concentration of methane, acid tests, hot water tests, the color and intensity of stain, fluorescence and residual cut were the only parameters monitored in mud logs. [21]

The early mud gas systems consisted in a low efficiency gas trap linked to a slow, low-resolution gas chromatograph. The data coming from these systems had limited applicability, it was only used to differentiate productive and non-productive formations.

However the improvements in the mud-logging field over the last years changed this old statement. The new advanced mud gas systems are producing reliable quality gas data, which is used for formation evaluation interpretation. Developments were performed on all mud gas logging aspect including: [14]

- More efficient mud gas extractors, which are less prone to drilling and mud property variables;
- Improvements in gas transfer lines to reduce liquid dropout;
- Modernized analytical devices from high resolution gas chromatographs (GC) to mass spectrometers;
- Early availability of analysis results enables a near real-time detection of seals and permeability barriers, lithological variations, and fluid contacts.

This new advent revealed advanced mud gas devices able to do quantitative extraction and characterization of light hydrocarbon gases. The analysis of such data enables the fingerprinting of the perforated hydrocarbon reservoir and the mapping of fluid facies prior to any kind of wireline log. Therefore the latest information, like fluid similarities, reservoir compartmentalization, et cetera, can be fed into the formation and sampling plan.

It is also important to stress the advantage of advanced mud gas analysis to assist the decision for the testing tool string design (sample volumes necessary for gas versus oil fluid evaluation program), help to choose the sampling points, and focus the formation evaluation program on any spotted anomaly. In the case of borehole instability or any other hostile circumstance that prevents the realization of wireline logging, advanced mud gas analysis may be the only formation evaluation tool available to provide hydrocarbon type information. [10]

The light gas ratios are the backbone of advanced gas analysis. The heavy gas ratios constitute the natural continuation and deepening of these, enriching the information obtained about the fluids and the reservoir. The following light gas ratios can give a first indication of fluid characterization, fluid contacts, fluid signatures, and abnormal situations:

- Haworth & Whittaker ratios (Characterization)
- Pixler ratios (Characterization / Signature)
- C1 Ratio (Characterization)
- Biodegradation Ratios (Evaluation / Contamination)

Haworth and Whittaker ratios

The most commonly used gas ratios versus depth are the Haworth and Whittaker ratios: wetness (Wh), balance (Bh) and character (Ch). These indicators help to identify formation fluid changes, therefore fluid contacts as gas-oil contact (GOC) or oil-water contact (OWC) can be estimated.

$$Wetness\ (Wh) = \frac{C_2 + C_3 + C_4 + C_5}{C_1 + C_2 + C_3 + C_4 + C_5} \times 100 \tag{1}$$

This ratio measures the proportion of heavy alkanes and indicates the density of the alkanes mixture contained in the potential bearing zone:

- If Wh < 0.5: dry gas with no or very low productive potential;
- If 0.5 < Wh < 17.5: potential productive gas;
- If 17.5 < Wh < 40: potential productive oil (oil gravity increases with Wh);
- If Wh > 40: heavy / residual oil with no or very low productive potential.

$$Balance\ (Bh) = \frac{C_1 + C_2}{C_3 + C_4 + C_5} \tag{2}$$

The balance ratio, presented in equation 2, measures the proportion of pure heavy alkanes versus pure light alkanes (methane and ethane) and is combined with the Wetness Ratio to improve the reliability of the interpretation:

- If Wh < 0.5 and Bh > 100: dry gas with no or very low productive potential;
- If 0.5 < Wh < 17.5 and Wh < Bh < 100: potential productive gas, with gas density increasing as the two curves converge;
- If 0.5 < Wh < 17.5 and Wh > Bh: potential productive condensates with high gravity oil;
- If 17.5 < Wh < 40 and Wh > Bh: potential productive oil. Oil gravity decreases as the curves diverge;
- If 17.5 < Wh < 40 and Wh >> Bh: heavy / residual oil with no or very low productive potential;
- If Wh > 40: not productive, very low gravity residue or/and water bearing zone.

Equation 3 presents the character ratio, which omits the lighter hydrocarbon compounds (methane and ethane) and just compares the heavier compounds. The presence of a dense hydrocarbon fluid can be confirmed and this should aid in the distinction of a very wet gas from a very high gravity oil.

$$Character\ (Ch) = \frac{C_4 + C_5}{C_3} \tag{3}$$

- If Ch < 0.5: Gas phase is confirmed, indicating either wet Gas or Gas Condensate;
- If Ch > 0.5: liquid phase is confirmed, so that the gas indicated by Wetness is associated with Oil.

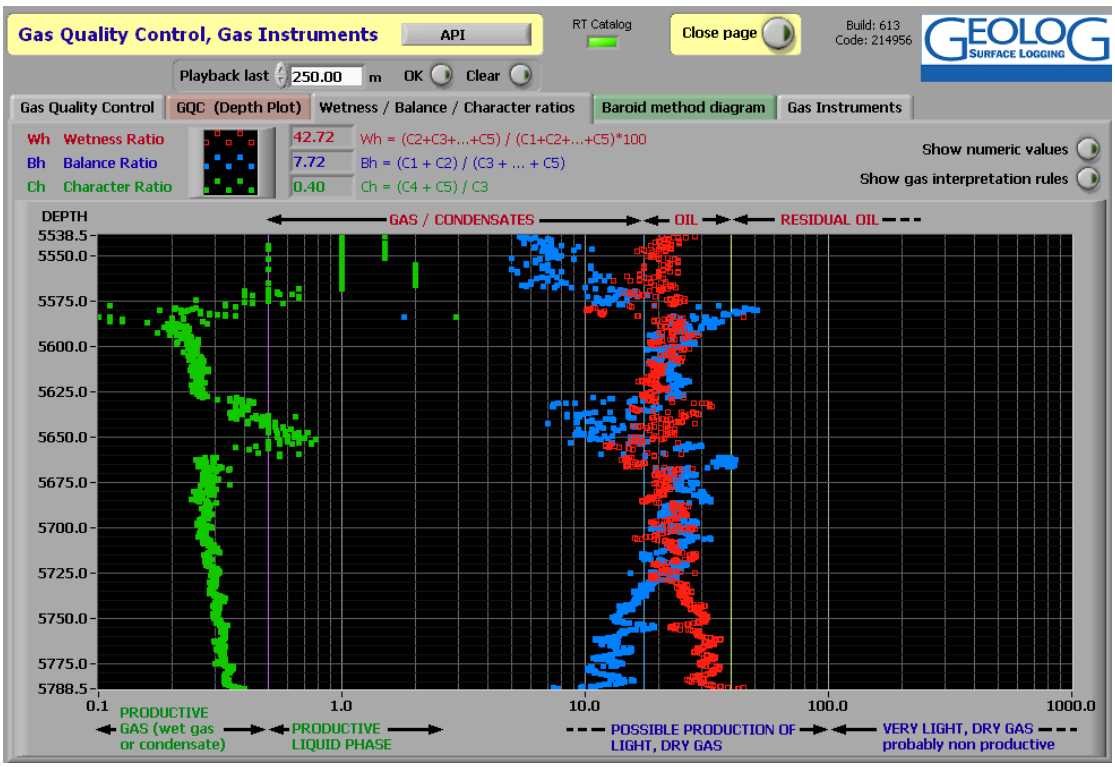


Figure 8 – Haworth and Whittaker ratios practical example, courtesy of Geolog.

Pixler Plot

Pixler plot is a series of ratios between methane and the other components. Pixler plots exist since the fifties, and they have always been used to recognize the signature of a formation fluid. Their significance has always been qualitative, but they help to differentiate one fluid from another with little doubt. The plot has some theoretical divisions, as presented in figure 9:

- C_1/C_2 > 35 and C_1/C_3 > 80 and C_1/C_4 > 200 - Dry non-associated gas;
- C_1/C_2 from 10 to 35 and C_1/C_3 from 15 to 80 and C_1/C_4 from 20 to 200 – Gas condensates;
- C_1/C_2 from 2 to 10 and C_1/C_3 from 2 to 15 and C_1/C_4 from 2 to 20 - Liquid Petroleum;
- C_1/C_2 < 2: Very low gravity, high viscosity, non-productive residual oil.

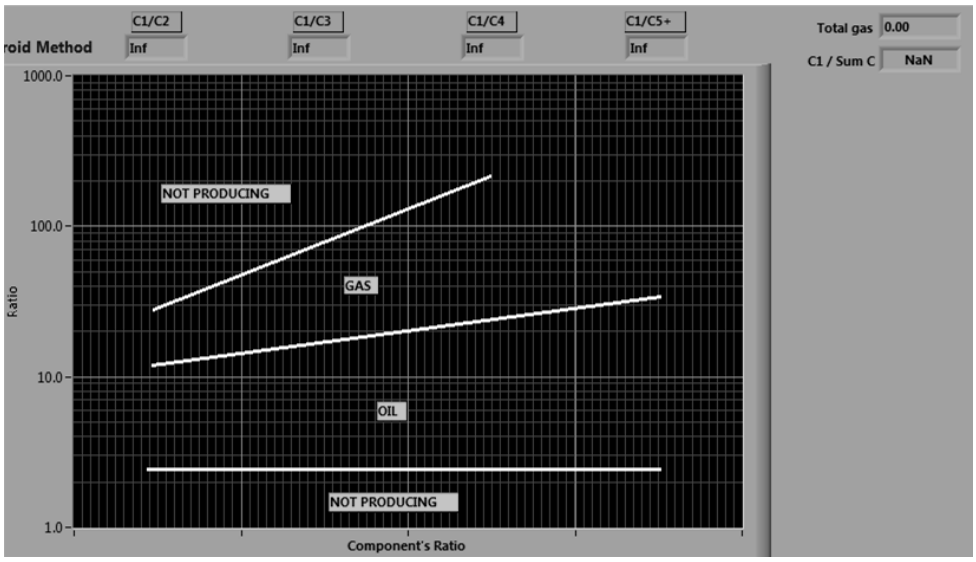


Figure 9 – Example of a Pixler Plot.

There is an important difference between Pixler plots and the other ratios reviewed so far. This plot has been designed specifically with the scope of analyzing the gas composition at single depth points. Therefore when plotting Pixler ratios, there is a need to pick targets (gas peaks). The procedure consists in identify them and obtain their composition from C_1 to C_5, or whatever is the heaviest component measured.

Some of the general interpretation rules for Pixler ratios are: the nearer is the curve to the X-axis, the denser the fluid in that point, and very high and steep curves normally indicate dry gas. It is also possible to identify the effect of gravity differentiation on the fluid if plotted several color-coding depths, as shown bellow in figure 10.

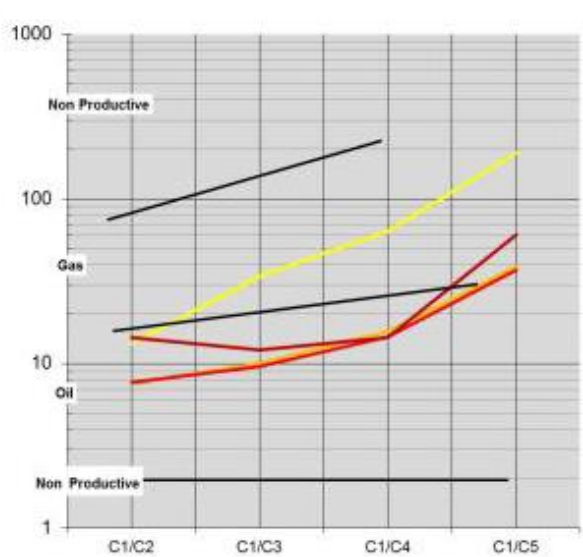


Figure 10 – Fluid gravity differentiation identification using a Pixler Plot. [5]

Additional light gas ratios

The C_1 ratio will tend to 1 when only methane is present and on the contrary, will decrease with the presence of heavier components. It will indicate the wetness of the gas, the fluid evolution, and the discontinuities in the reservoir. When the distribution of points is very casual, it means that hydrocarbons are not present in sufficient quantities for a proper evaluation. Two interpretation examples can be observed in figure 11.

$$C_1(\%) = \frac{C_1}{C_1 + C_2 + C_3 + C_4 + C_5} \tag{4}$$

This ratio can also be used also for fluid characterization:

- C_1 / (C1 + C_2 + C_3 + C_4 + C_5) > 0.95 - dry gas (CH4) Bacterial;
- 0.85 < C_1 / (C1 + C_2 + C_3 + C_4 + C_5) < 0.95 - possible productive gas;
- 0.6 < C_1 / (C1 + C_2 + C_3 + C_4 + C_5) < 0.85 - possible productive oil;
- 0.6 > C1 / C1 + C2 + C3 + C4 + C5 - possible residual oil.

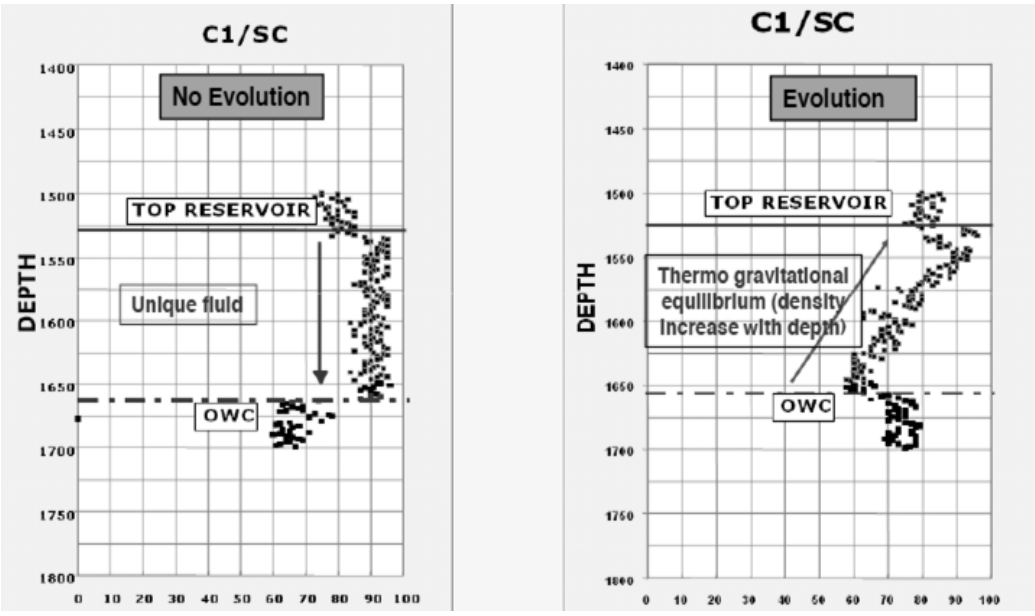


Figure 11 – Example of C_1 ratio application. [25]

The biodegradation ratio is based on the fact that bacteria preferably attack the straight chain alkanes, rather than the branched chain. So whenever the ratio iC_4/nC_4 or iC_5/nC_5 is bigger than 1, it is valid to infer that formation fluid was biodegraded.

$$Biodegradation\ Ratios = \frac{iC_4}{nC_4}\ ;\ \frac{iC_5}{nC_5} \tag{5}$$

2.2. Datasets and methodology

The fluids datasets used in this project are from eight different wells drilled under different conditions around the world. The companies name, depth information and geographical coordinates were removed from the datasets in order to prevent data identification.

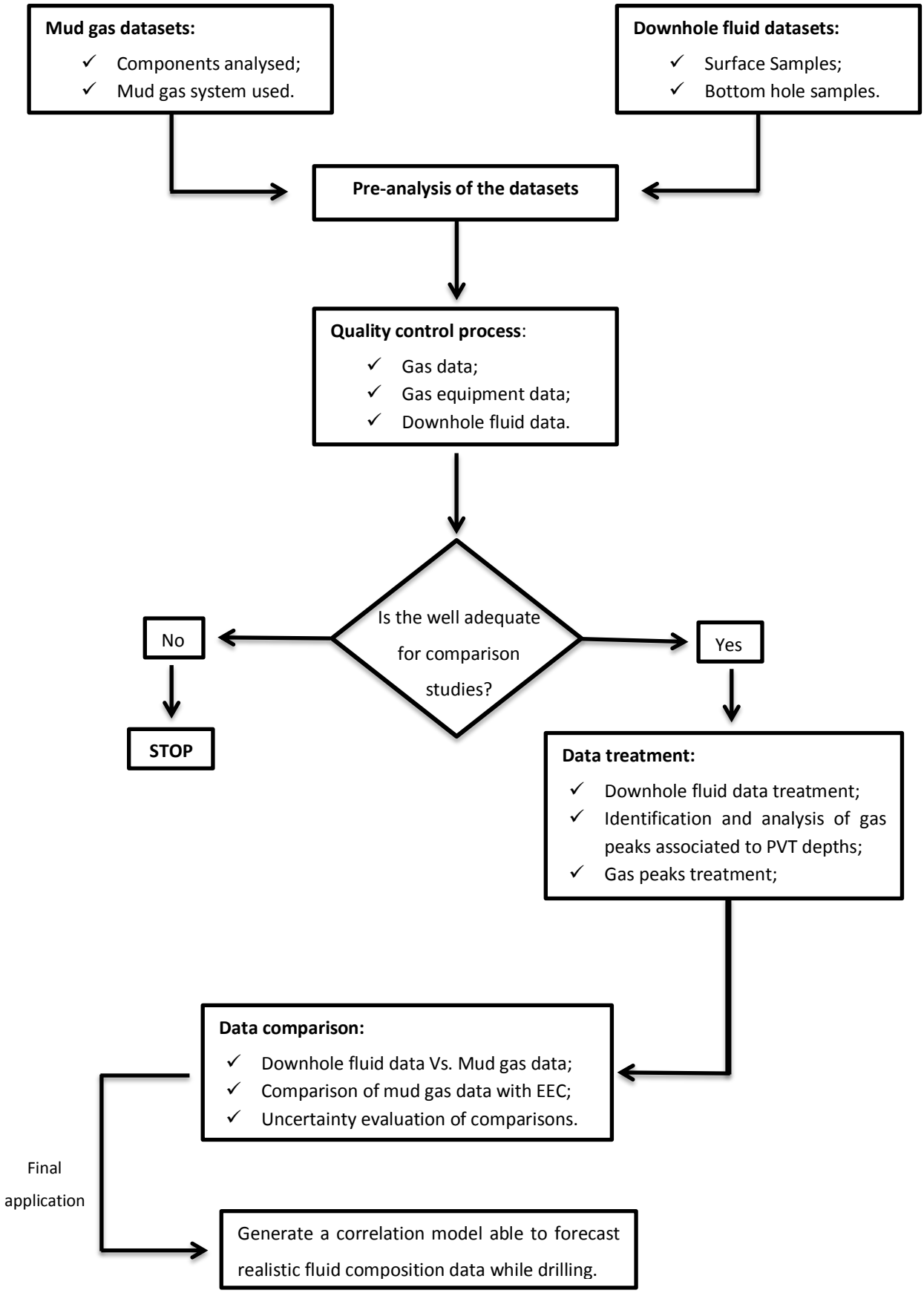
For each well was available the gas log recorded by the mud logging company, and the downhole fluid information acquired during well tests. It is important to stress that different techniques were used to collect and analyze both fluids. In this way it is crucial to start by doing a quality control check on the datasets of the data collection and analysis procedures.

The adopted methodology for this study started with a pre-analysis of the datasets, to review how each sample was collected and how it can influence the data quality. The next step was a quality control check on the mud gas, downhole fluid and gas equipment data.

The main stage of this research started with the treatment of the datasets in order to become comparable measurements. Once achieved, the next step was the selection of data for fluid composition comparison and the associated uncertainty study.

The ultimate goal was the development of a linear model able to predict, in near real time while drilling, the downhole fluid composition based on the mud gas shows at surface.

The proposed workflow for this project is summarized in the next page:


Mud gas datasets:
✓ Components analysed;
✓ Mud gas system used.
Downhole fluid datasets:
✓ Surface Samples;
✓ Bottom hole samples.
Pre-analysis of the datasets
Quality control process:
✓ Gas data;
✓ Gas equipment data;
✓ Downhole fluid data.
Is the well adequate for comparison studies?
No
STOP
Yes
Data treatment:
✓ Downhole fluid data treatment;
✓ Identification and analysis of gas peaks associated to PVT depths;
✓ Gas peaks treatment;
Data comparison:
✓ Downhole fluid data Vs. Mud gas data;
✓ Comparison of mud gas data with EEC;
✓ Uncertainty evaluation of comparisons.
Final application
Generate a correlation model able to forecast realistic fluid composition data while drilling.

2.3. Surface gas data collection

The acquisition of gas data while drilling for geological surveillance and safety is almost a universal practice. Mud logging crew utilizes a gas extractor to agitate re-circulated drilling fluid in order to release the gas contained in it. The liberated gas is guided to a gas chromatograph to analyze the gas composition.

The quality of the measurements is limited by the mixture of extracted gas with air in the gas trap and by the unmeasured entrained formation gas that remains in the drilling fluid. Heavier components are more prone to remain in oil-based or synthetic-based drilling fluids, which creates additional analysis uncertainties.

This source of data is rarely used for formation evaluation due to the widely accepted presumption that it is unreliable and unrepresentative. Nevertheless recent developments in the mud logging industry have improved acquisition and analysis techniques that led to the availability of better quality data.

The classic gas chain, as represented in figure 12, contains a gas trap; a series of filters in order to remove water, particles and other impurities from the gas; a distribution system to supply different gas instruments and gas analyzers.

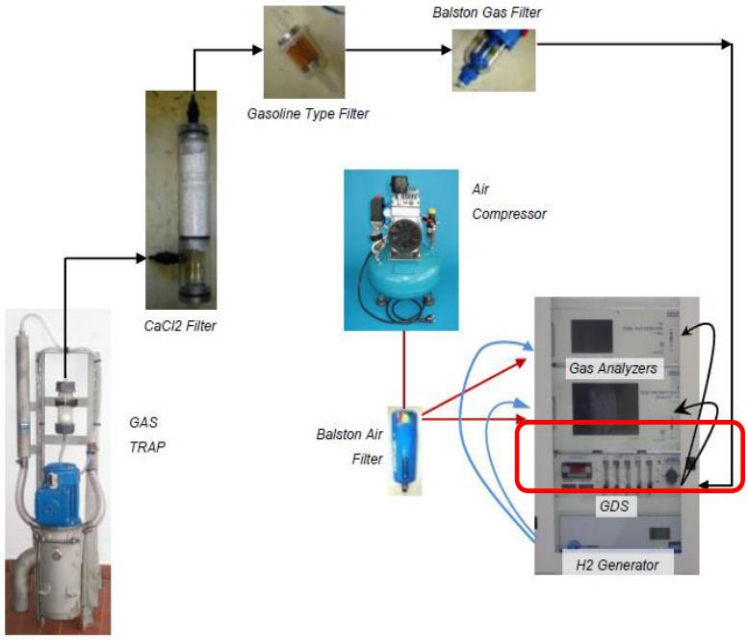


Figure 12 – Basic gas system, courtesy of Geolog.

2.3.1. Basic gas extraction principles

The basic gas extractor, quantitative gas measurement (QGM), extracts gas from the mud and mixes it with air, as represented in figure 13. The air carries the gas to the gas detectors, this is why it is called gas-in-air. The percentage of gas-in-air does not correspond to gas-in-mud in a quantitative way. It depends on the extraction method, on the efficiency of the agitator, and on the rate of dilution of the gas sample.

Mud logging companies have gone a long way to ensure that gas-in-air and gas-in-mud are strictly related, however the quantification of gas in mud is still difficult. Nevertheless, the percentage of gas-in-air is still very useful to evaluate the relative variation of gas.

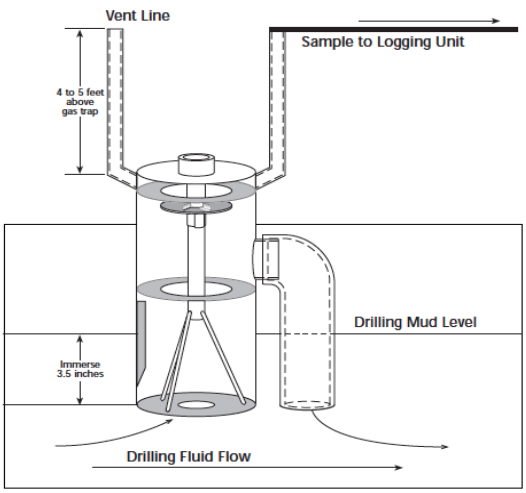


Figure 13 – Gas trap – Quantitative Gas Measurement, courtesy of Geolog.

The idea of quantitative gas measurement was born, in the early nineties. Texaco not only developed the QGM gas trap, but also worked out a way to reference the gas trap readings to the real gas content of the mud. This was done using mud stills and plotting the results of QGM gas extraction with the distilled gas taken from the mud sample.

The chart presented in figure 14, was obtained collecting data from numerous wells from various regions, drilled with different muds, shows an acceptable correlation between the gas values measured by mud logging systems and those deduced by distilling the mud. The rule of thumb suggests that any reading seen from a QGM gas trap is going to be approximately 5 times higher than the real gas-in-mud concentration.

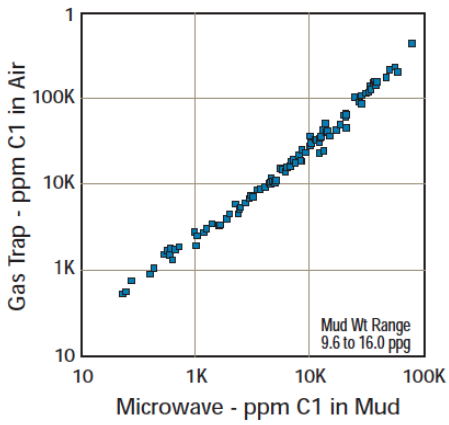


Figure 14 – Relationship between gas-in-air and gas-in-mud. [26]

This ratio is not valid anymore when the gas levels are very low (below 500 ppm) or very high (above 20%) because at high levels, gas escapes in the bell nipple and flowline and it is impossible to quantify how much of it is lost before the mud reaches the extraction point.

Gas-in-mud is the volumetric percentage of gas in a volume of mud. It can be obtained from gas in air if it has been extracted and analyzed with an advanced gas detection system and if the value has been corrected by the specific extraction efficiency coefficient (EEC), which will be described later on in this chapter.

The possibility of a gas cut and the subsequent hydrostatic pressure reduction at the bottom of the well is a risk that should be minimized. For drilling purposes, the best way to monitor this issue is a precise measurement of drilling fluid density, which gives a clear indication of any significant gas cut, as illustrated in figure 15.

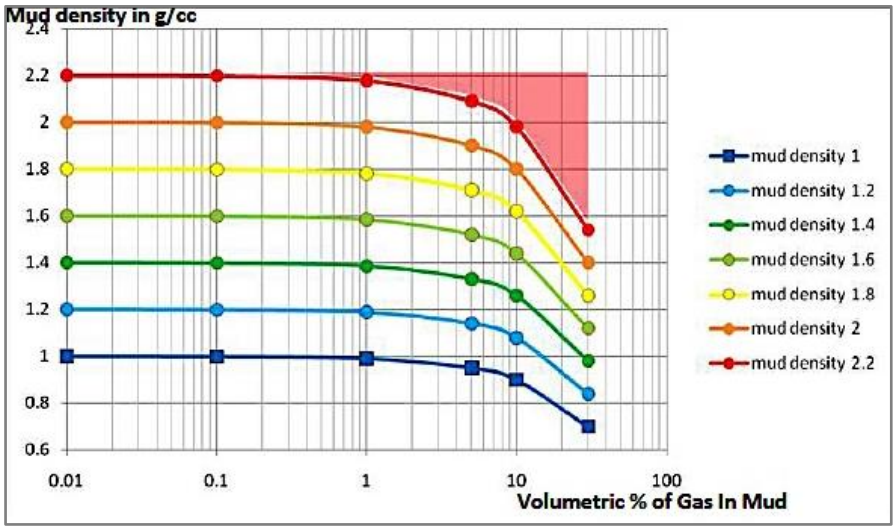


Figure 15 – Relationship between gas-in-mud and resulting mud density cut, courtesy of Geolog.

Geolog developed another gas extractor called constant volume degasser (CVD), presented in figure 16. The CVD is a system able to extract a gas sample from a constant volume of mud regardless of the drilling fluid flow rate and the variations in the mud level. The working principle is based on the suction of a certain volume of mud per minute using a peristaltic pump.

The amount of gas sample extracted from the mud is influenced only by the downhole conditions, since the volume of mud centrifuged is constant. The gas extracted merges with air in the upper part of the bowl and then a membrane pump forces it out with a constant flow rate to the gas distribution system (GDS). From the GDS the gas flow is distributed with constant flow rates to the different gas detectors.

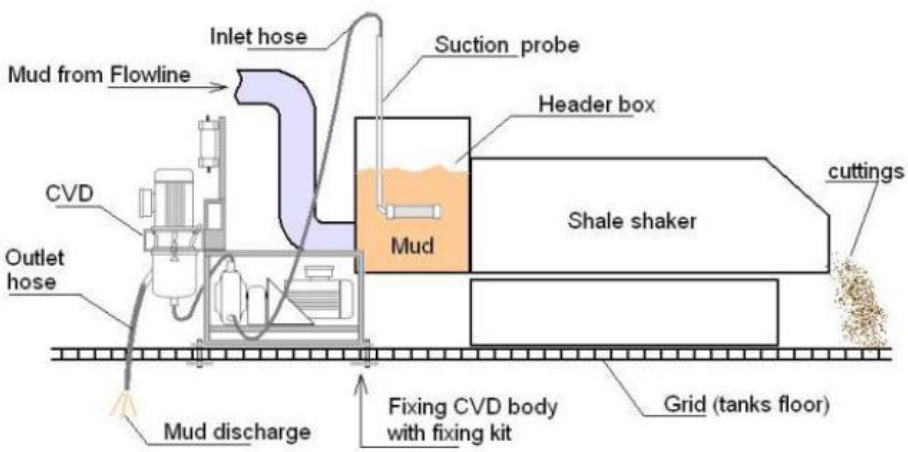


Figure 16 – CVD installation, courtesy of Geolog.

2.3.2. Detection and identification of mud gas

Considering the whole spectrum of a typical hydrocarbon fluid composition, the fraction of hydrocarbons typically detected while drilling corresponds to the very lightest (red area in the figure 17). Even extending the research to the heavier gases, the analysis only detects a minority of compounds (orange area).

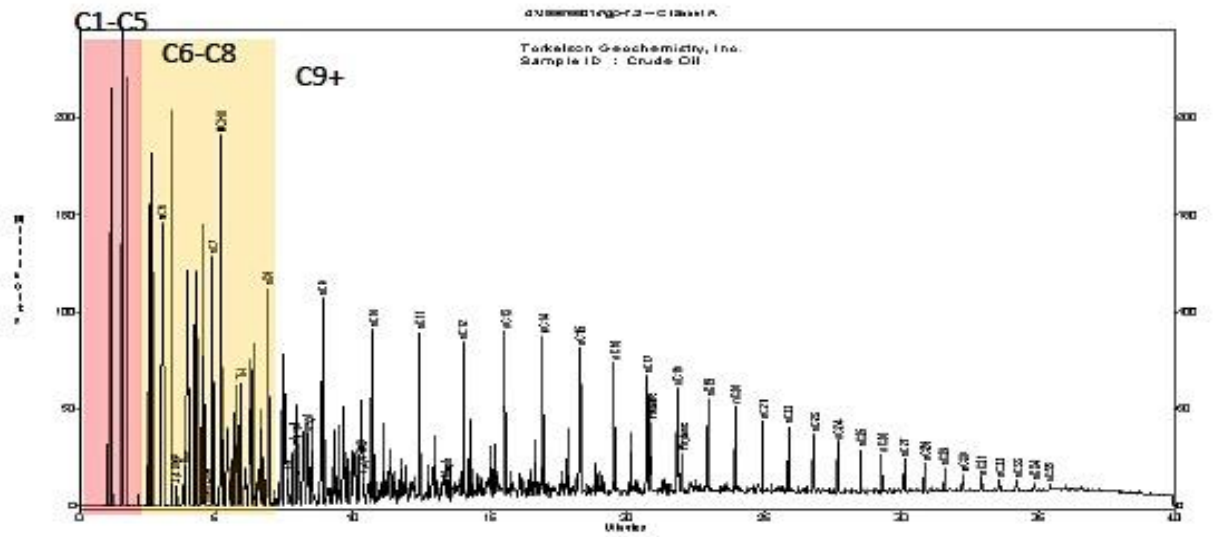


Figure 17 – Spectrum of a typical hydrocarbon fluid composition, courtesy of Geolog.

The separation and analysis of the light gas fraction in *Geolog* is invariably done with *DualFid* chromatograph. Light hydrocarbons are the main gas components in terms of abundance and tend to be in gaseous state at surface pressure and temperature, as presented in table 1.

The chromatographic columns separate the gases in an order that is largely dependent on their boiling point, the ones with the lowest boiling point elute faster. This generally corresponds to the molecular weight, so smaller molecules will elute faster through a chromatographic column compared to heavy ones. The *DualFid* system utilizes a double column in order to split in different lines the very light gases (methane and ethane) from the light gases.

Table 1 – Properties of the light hydrocarbons analyzed by *DualFid,* courtesy of Geolog.

Compound name	**Number of carbons atoms**	**Chemical formula**	**Boiling point (ºC)**	**Fluid state at 20ºC & P_{atm}**	**Reference name**
Methane	1	CH_4	-162	Gas	C1
Ethane	2	C_2H_6	-89	Gas	C2
Propane	3	C_3H_8	-42	Gas	C3
i-Butane	4	C_4H_{10}	-13	Gas	iC4
n-Butane	4	C_4H_{10}	0	Gas	nC4
i-Pentane	5	C_5H_{12}	28	Liquid	iC5
n-Pentane	5	C_5H_{12}	36	Liquid	nC5

Other hydrocarbons such as non-saturated alkenes or alkynes are generally not found in fossil hydrocarbon fluids. The main reason is that over time all the hydrocarbons tend to their saturated form, which are mainly alkanes.

Alkenes, however, can be found as contaminants while drilling. In fact, some drilling fluids, when exposed to high temperatures, as is the case when drilling with downhole motors, can liberate alkenes. This generates a problem because light alkenes (ethene and propene) have the same chromatographic elution time as ethane and propane. At this time it is possible to quantify the presence of alkenes utilizing either a gas chromatograph mass spectrometer, or a dedicated alkenes flame ionization detector (FID) able to measure both ethene and propene.

Things become more complex in the spectrum of heavier components, because they have many isomers and some of them are very difficult to separate chromatographically. For these heavier hydrocarbons is used a slower chromatography with a different type of column.

In the investigation interval, between n-Pentane and Toluene, there are approximately thirty gas species. Some of them have almost identical elution times, and invariably appear as a single peak. Therefore Geolog decided to focus the heavy gas detection on the most abundant and representative compounds, which are presented in table 2.

Table 2 – Properties of the heavy hydrocarbons detected by *DualFid Star, courtesy of Geolog.*

Compound name	**Number of carbons atoms**	**Chemical formula**	**Boiling point (ºC)**	**Fluid state at 20ºC & P_{atm}**	**Hydrocarbon type**
n-Hexane	6	C_6H_{14}	68	Liquid	Alkane
Benzene	6	C_6H_6	80	Liquid	Aromatic
Cyclohexane	6	C_6H_{12}	81	Liquid	Naptene
n-Heptane	7	C_7H_{16}	99	Liquid	Alkane
Metylcyclohexane	7	C_7H_{14}	101	Liquid	Naphtene
Toluene	7	C_7H_8	111	Liquid	Aromatic

Chromatography enables to identify and isolate many of these species or groups of gas species, as well as to utilize the respective abundances and ratios recorded in the mud gas to infer information about the hydrocarbon fluid contained in the reservoir, the reservoir itself, the source rock and its maturity. [10]

2.3.3. Gas shows classification

The standard gas shows classification proposed by Mercer [16] is still used, since the principles of gas liberation have not changed, only the technologies used to detect have been upgraded. The main gas shows categories identified are:

1. Liberated gas: gas mechanically liberated by the bit into the drilling fluid as the bit penetrates the formation.
2. Produced gas: gas influx from the formation into the drilling fluid. Formation pressure exceeds the opposing effective mud hydrostatic pressure.
3. Recycled gas: gas that has been pumped back down the hole therefore will appear a second time at the surface.
4. Contamination gas: gas artificially introduced in the drilling fluid system from a different source than rock formations.

The next figure illustrates a typical situation where a well is drilled through a hydrocarbon bearing zone and the total bottomhole pressure (TBP) is greater than the formation pressure (FP). Under these conditions the primary source of hydrocarbon gas derives from the cylinder of rock crushed by the bit action. Figure 18 shows the typical liberated and recycled gas response for these conditions.

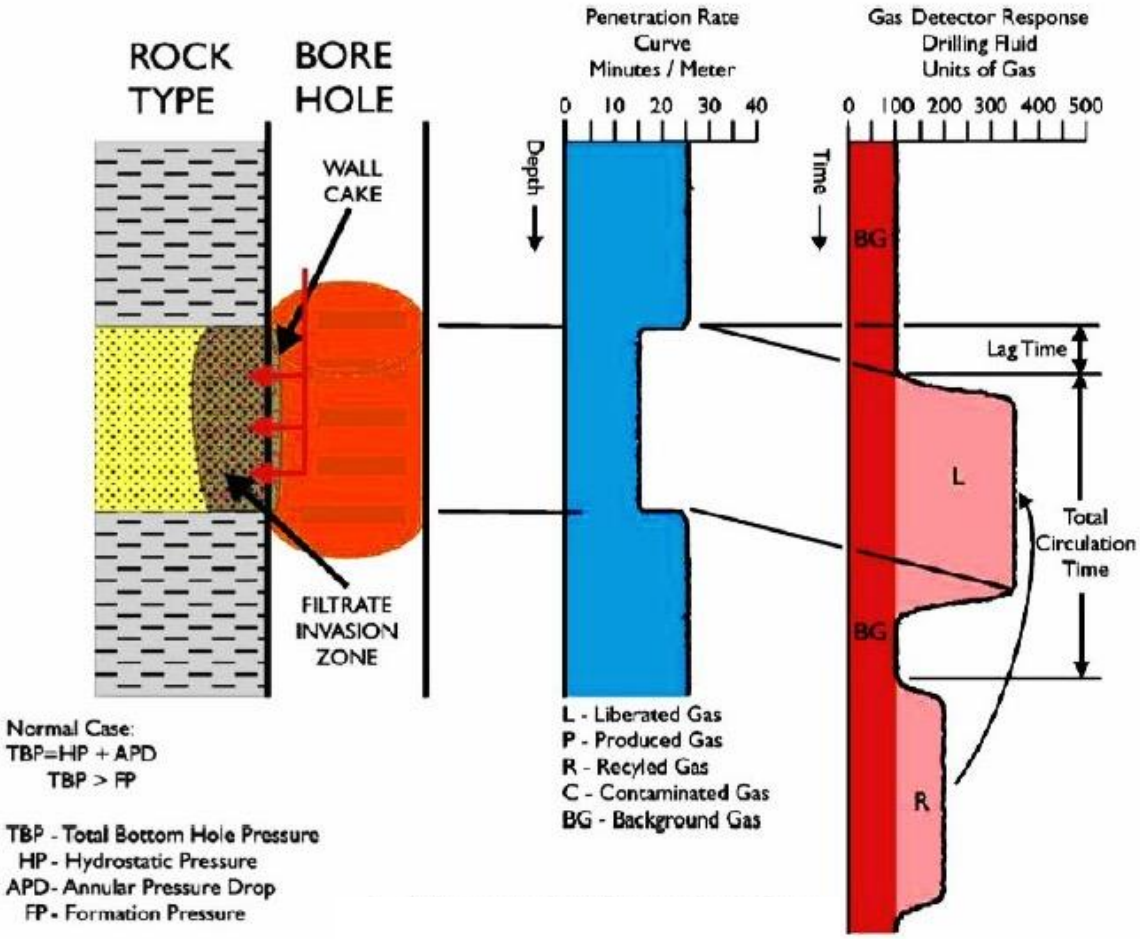


Figure 18 – Liberated and recycled gas response [15]

In fact, porosity will ultimately determine the amount of gas seen on surface, permeability will not necessarily have a significant effect. If there is no effective permeability when drilling a hydrocarbon bearing zone, the liberated gas show will still occur.

In the event that mud gas is not completely volatilized in the settling pit but is pumped back down the hole, the gas detector may record a second appearance of a pre-existing show. This phenomenon is illustrated in the previous figure where the liberated gas show has recycled to the surface for the second time and is designated R. The total circulating time of the mud system can be estimated from the beginning of the primary gas response to the beginning of the recycled gas response. Such direct information may often be helpful in assuring the accuracy of an estimated lag time.

The figure 19 illustrates the abnormal case where the total bottomhole pressure is less than the formation pressure. The gas response resulting from such situation is characterized by significant differences from those previously discussed and is designated produced gas response.

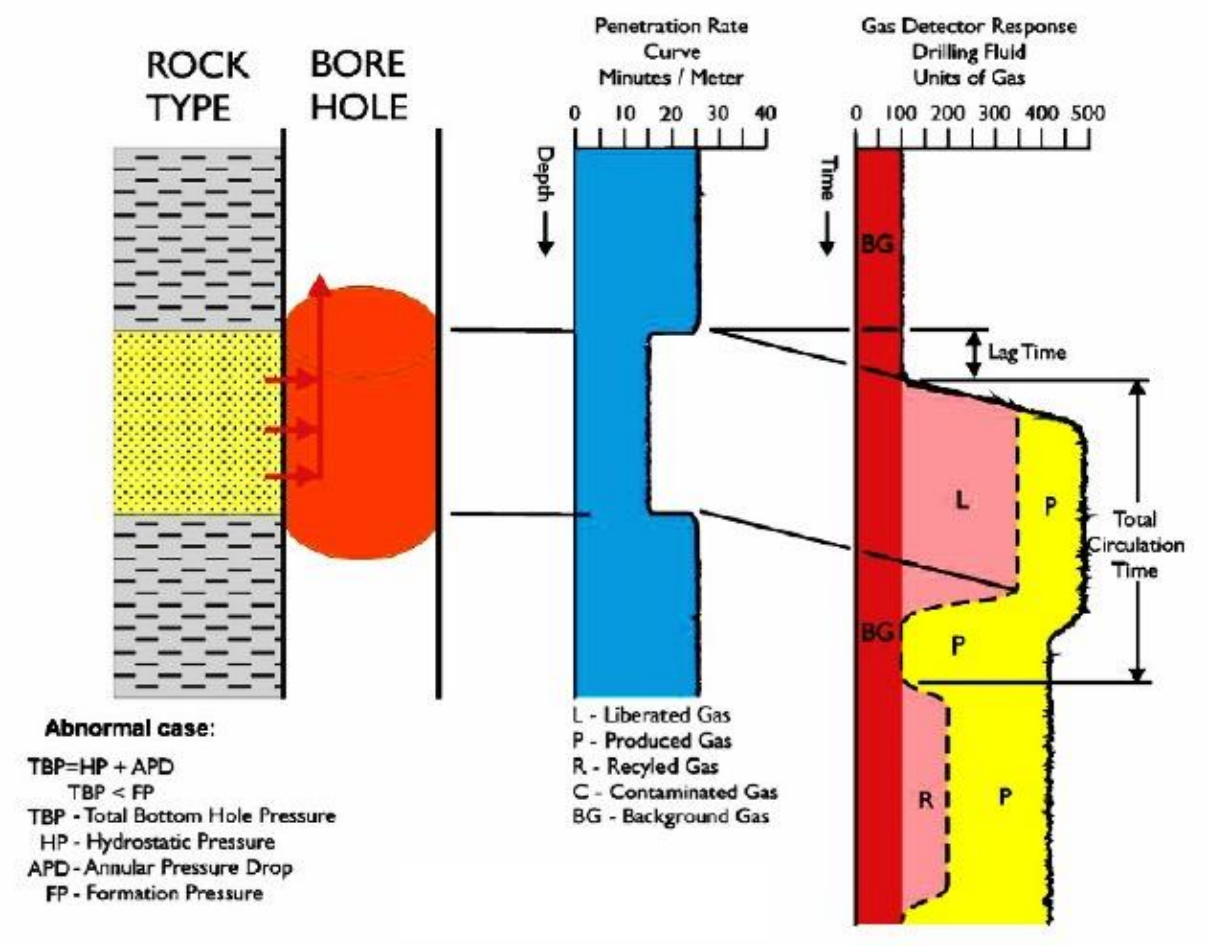


Figure 19 – Produced gas response [15]

If the source zone is clearly defined by the penetration rate and other available geological data, it becomes evident that formation is contributing with additional hydrocarbons to the mud system beyond those mechanically liberated. The colour-coded log on the right shows the extent and the role of different contributors to the gas reading: the background gas already present in the mud, the liberated and recycled gas (in pink) and the produced gas (in yellow). In reality, if the formation is underbalanced, the yellow portion will tend to increase progressively and a well control situation will arise.

Contamination gas occurs when drilling operations require the introduction of oil or other additives in various forms to provide additional pipe lubrication, wellbore stability and inhibition, et cetera. Some contaminants, as diesel, will only affect the total gas reading with heavy volatile gases, since the basic chromatograph is only sensitive to the lighter gas species. Moreover, the presence of certain asphaltic products, will affect heavy hydrocarbons content, generating an artificial background that must be taken into account when analyzing the data.

2.3.4. Factors influencing gas readings

The changes in the gas readings in open hole happen due to different factors. Some of them are natural, and others originated by the drilling process. Nevertheless, some of these factors can be controlled, and, their effect minimized.

The most important category for interpretation purposes are the natural factors, as the amount of gas present in the rock and the rock porosity. On the other hand, the man-made factors should be taken into account and, if possible, mitigated. Some of these factors are the difference of pressure between formation and ECD, the bit diameter, the rate of penetration (ROP), the pump rate, the mud temperature and the mud type.

The gas measurement characteristics should also be considered. Factors like the amount of mud stirred by the gas trap in a given time, the positioning of the gas trap or the calibration of the gas detector have a huge influence in gas readings.

All the above contribute to inaccurate gas reading that will be obtained by the detection system. These factors are taken into account in order to minimize the impact in the final outcome. The ideal result is a gas reading that is exclusively dependent of natural factors.

To achieve the aforementioned goal some solutions and countermeasures can be applied. Some of these measures are:

- The difference of pressure between formation and equivalent circulating density. For all formation evaluation purposes, it is always better to try and work with a mud weight that is just above the formation pressure;
- The drilling parameters can be taken into account calculating the normalized gas using equation number 6;

$$Normalized\ gas = 1{,}1845\ \times \frac{ROP\ \times\ Total\ gas\ \times\ Flow\ rate}{Bit\ diameter} \tag{6}$$

Bit diameter – inches
Flow rate – liters/minute
Total gas - %
ROP – meters/hour

- The only way to maintain the mud temperature high enough and constant throughout a drilling phase is to utilize a mud heater;
- The gas trap capacity, this issue can be solved by fixing a mudflow through the extraction cup;
- The calibration data must always be available and up to date, to ascertain that the detectors are operating correctly.

The application of all the above correction and mitigation techniques will deliver a high-quality gas data. In reality, at least one relevant factor is still out of control. The dispersion of gas occurring at the bell nipple, when the drilling fluid reaches surface, cannot be measured. It is possible that, in the presence of large gas shows, a significant data loss occur. The most obvious solution is installing the probe of the gas extractor directly onto the conductor pipe, although technically simple, has not yet been tried.

2.3.5. Advanced gas chain

Geolog runs a very well accomplished advanced gas detection system. This system has received the approval from the clients for the quality of gas data, which is helping them with their formation evaluation studies, at a cost that is a fraction of logging while drilling or wireline data.

In the next figure it is possible to understand the chain of the advanced gas system.

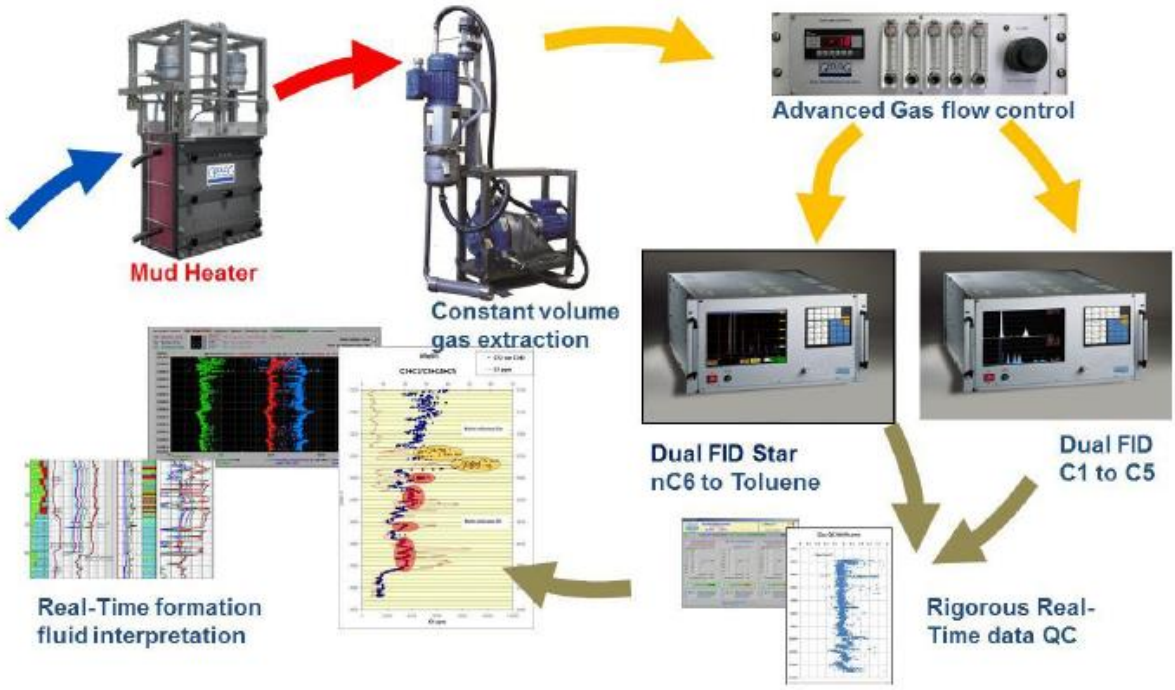


Figure 20 – Advanced gas chain [3]

1. Constant volume gas extractor - This type of extractor enables to assure the repeatability of the reading and removes one of the main interferences in gas data quality, which are the variations in mud level and flow.
2. Mud heater - Since gas extraction is dependent on gas solubility, which decreases rapidly with low temperatures, a mud heater guarantees that gas level changes are not related to surface temperature change.
3. A constant flow control sample distribution system - Without such system, the gas sample going to the detector would be influenced by external factors such as temperature, sample density, and pressure losses along the gas sample line, jeopardizing reading repeatability.
4. A high-resolution light gas analyzer - This detector has a double chromatographic column, which separates the ultra-light hydrocarbons on one side, enabling ideal separation of C_1 from C_2, and the fraction from C_3 to C_5 on the second column. This solution achieves the ideal compromise between speed of analysis and accuracy.
5. A *DualFid Star* chromatograph, with the same FID detector and a capillary column able to separate six heavier hydrocarbon gases (n-hexane, cyclohexane, benzene, n-heptane, methyl-cyclohexane, toluene) from other species and recognize contaminants, which may be present in the fluid.

6. A real-time automated gas data QC system - This software constantly compares the gas data readings from separate instruments, and raises a flag when the data do not match, enabling a quick response to the problem.

7. A dedicated gas analysis software package - This software is used offline by the field specialist to make the most of the gas data.

2.3.6 Extraction Efficiency Coefficient (EEC)

Mud gas data normally does not correspond to the gas values measured by the clients during production tests or when taking formation PVT samples. The main reason is that the degasser extraction efficiency is not perfect, so not all gas entrained in the mud is extracted in this process.

However, if it is feasible the estimation of an extraction efficiency, then it is possible to apply it to our gas shows and correct the composition value. This correction will bring gas readings much closer to the PVT composition.

It is possible to conceptualize that the various gas species concentration decrease but not at the same rate. C_1 is degassed more efficiently than C_2, C_2 more than C_3, et cetera. This proves that heavier components have a low extraction efficiency coefficient.

2.4. Downhole fluid data collection

The sampling purpose is to obtain a representative sample of reservoir fluid, which means identical to the initial reservoir fluid. This condition is absolutely essential because reservoir engineering studies, which are performed using pressure volume and temperature (PVT) analysis data, are always made on the basis of the reservoir at its initial conditions. For this reason, sampling operations should ideally be conducted on virgin reservoirs (having not yet produced) or in new wells completed in undepleted zones, containing fluids identical to the initial reservoir fluids.

Nevertheless, if sampling cannot be performed at initial conditions, or if for any special reason samples have to be taken in a well that has already produced a sizeable amount of oil, the reservoir and production data should be carefully analyzed. If the production fluids are still identical to the initial fluids, the sampling procedure will be very similar to the one performed on new wells. On the other hand, if the produced fluid is not identical to the fluid initially in place in the reservoir, one cannot hope to obtain representative samples. [21]

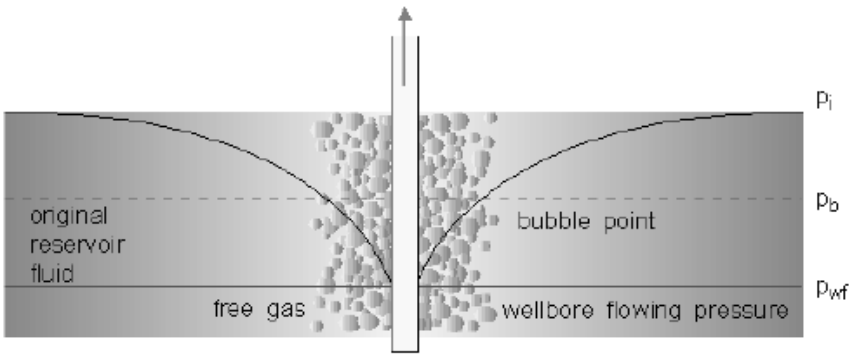
2.4.1. Representative samples

A representative sample is a sample that has the same qualitative and quantitative composition as the original fluid. Meaning that from qualitative point of view the collected sample should contain the same molecules as the main fluid when at reservoir conditions. Quantitatively, this portion of fluid sample must contain the molecules in the same molar fractions.

For decades service companies have been challenged by this objective to design and make tools, sampling chambers and techniques that can address different reservoirs and get a sample of different natures from the borehole or directly from an open hole section probed to the reservoir. [21]

The pressure drawdown associated with flow will often be sufficient to drop the pressure of the fluid in the surrounding wellbore area below its bubble point or dew point pressure and into the two-phase region, as illustrated in case 1 of figure 21. Sample of such fluid will not be representative of the original reservoir fluid. Steps must be taken to determine the reservoir pressure, temperature, and the general category of the reservoir fluid. If the relationship between reservoir pressure and bubble point or dew point pressure can be estimated, actions can be taken to ensure that the sampled fluid is representative.

Case 1 – Fluid pressure bellow bubble point pressure



Case 2 – Fluid pressure above bubble point pressure

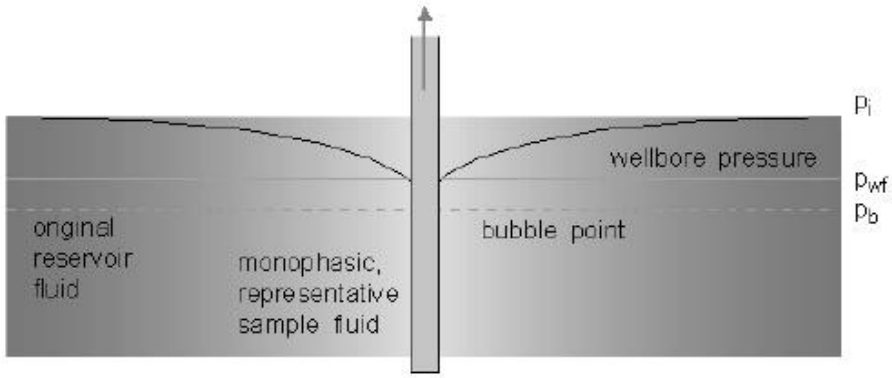


Figure 21– Diagram of pressure distribution within the formation [21]

2.4.2. Producing conditions and well conditioning

The producing conditions and surface or subsurface equipment can be important considerations when planning a sampling procedure. The most important of these are:

- The type of fluid being sampled;
- The stability and accuracy of gas rate, oil rate, and gas oil ratio measurements;
- The proximity of gas-oil or oil-water contacts to the sampling interval;
- Whether the well is a flowing or pumping well;
- The dimension of downhole equipment;
- The well location.

Dry gas reservoirs and highly undersaturated oil reservoirs, where the produced fluids remain in a single phase under any flowing conditions (including surface conditions), are relatively easy to sample on surface. An oil reservoir at or slightly above the bubble point will undoubtedly yield free gas at bottom hole flowing pressures and require conditioning prior to sampling.

Conditioning is a procedure where production rate is gradually reduced, resulting in successively higher flowing bottomhole pressures. This simultaneously removes the altered fluid from near the wellbore and moves fresh, unaltered reservoir fluid into the pores. If samples of oil and gas are taken at the surface, it is vital that the producing rates and gas-oil ratio be accurately determined in order that the fluids may be recombined in the correct ratios to formulate a representative sample.

The objective of well conditioning is to replace the non-representative reservoir fluid located around the wellbore with original reservoir fluid by displacing it into and up the wellbore. A flowing oil well is conditioned by producing it at successively lower rates until the non-representative oil has been produced. The well is considered as conditioned when further reductions in flow rate have no effect on the stabilized gas-oil ratio.

The duration of the conditioning period depends upon the volume of reservoir fluid that has been altered as a result of producing the well below the bubble point pressure, and how quickly it can be produced

at low rates. Most oil wells that have not been produced for a long period of time require little conditioning. However, some wells may require up to a week of conditioning to achieve stable gas oil ratios.

After conditioning the well, samples may be taken with a bottom hole sampling device, or individual samples of oil and gas may be taken at the surface and recombined to obtain a representative reservoir fluid sample. The choice of sampling technique is influenced by [23]:

- The volume of samples required;
- The type of reservoir fluid to be sampled;
- The degree of reservoir depletion;
- The surface and subsurface equipment.

Bottomhole sampling is the trapping of a volume of fluid in a pressurized container suspended on wireline inside the well, close to the productive interval. This method is used when:

- Only a small volume of fluid is required;
- The oil to be sampled is not so viscous;
- The flowing bottomhole pressure is known to be greater than the reservoir oil saturation pressure;
- The subsurface equipment will not prevent the sampler from reaching the appropriate depth or make its retrieval difficult.

Surface sampling consists in taking samples from the oil and gas separator, along with accurate measurements of their relative rates, and reconstructing a representative sample in the laboratory. This method is often used when:

- A large volume of both oil and gas are required for analysis (as in the case of gas condensate fluids);
- The fluid at the bottom of the well is not representative of the reservoir fluid (gas condensate reservoirs and oil reservoirs producing large quantities of water).

The main difficulty, while sampling on surface, arises from the fact that liquid and gas are in dynamic equilibrium inside the separator. Any drop in pressure or increase in temperature of the liquid separator, which is at bubble point, will result in the formation of gas. For the gas separator, which is at dew point, any increase in pressure or decrease in temperature will result in the condensation of heavy components.

Normally, a bottomhole sample is preferred if gas and oil surface measurement capabilities are in question. However, if they are reliable, the surface sampling technique can give a statistically valid value of GOR measured over a long period of time. Whenever possible, liquid and gas separator samples should be taken simultaneously in order to have the same sampling conditions for both fluids.

2.4.3. Sampling techniques

A PVT sample can be taken from a bottomhole sample or from a surface sample. Different techniques can be used, as Modular Formation Dynamics Tester (MDT), Drill Stem Test (DST), or surface separators. In general, a bottomhole sample has oil and gas components in a single phase because they are collected at saturation pressure. The surface sample instead has oil and gas already separated.

Surface sampling – The advantage of sampling at surface conditions using a separator is mainly the fact that the sample taking process can be controlled more exactly, and there are no restrictions on sample volumes. Separator sampling is considered the best method for a reservoir fluid close to or at the saturation pressure (either bubble point or dew point).

A DST is a procedure for isolating and testing the pressure, permeability and productive capacity from a section of a drilled well. The test is an important measurement of pressure behavior and it is a valuable way of obtaining information on the formation fluid and establishing whether a well has found a commercial hydrocarbon reservoir.

During the DST, a set of packers is run into the hole to isolate the well section that is subject to the test. The packers are inflated above and below the section to be tested. Once the packers are set, a valve is opened, reducing the pressure in the drill stem to surface pressure, causing fluid to flow out of the packed-off formation and up to the surface. The surface sample collected through a DST is inevitably a two-phase fluid. Fluid samples should be collected from both co-existing phases and recombined at the producing ratio.

Bottomhole sampling – Downhole samples, commonly referred as bottomhole samples, are the most representative of the original formation fluid, because they are collected as close to reservoir pressure and temperature as wellbore conditions permit. Bottomhole samples are taken with devices deployed on wireline or slickline called modular formation dynamics testers, or as an integral part of the DST toolstring.

The most important success factor for obtaining representative reservoir fluid samples is to maintain the fluid in single phase during sampling and transfer. This can be accomplished by accurately controlling the sample drawdown pressure and keeping it above the saturation pressure and as close to the reservoir conditions as possible.

For some fluids, the saturation pressure increases with decreasing temperature. A large drawdown during sampling and subsequent temperature drop could increase the saturation pressure to above the reservoir pressure, resulting in liquid drop out (two-phase flow), and therefore, non-representative fluid samples would be collected. [21]

Bottomhole single-phase samplers can be wireline conveyed or run inside of a dedicated drillpipe conveyed sampler. These samplers offer a cost-effective solution for obtaining samples when precipitation will occur during the flow to the surface.

2.4.4. Fluid analysis and uses of data

The composition and physical properties of produced fluids critically impact completion designs, flowline, separation and pumping stations, and even processing and refining plants - especially when CO_2, H_2S or other corrosives gases are produced. Compositional analysis provides a key input for the field development plan. [17]

As soon as the samples arrive at the PVT laboratory the first thing that is done is to check their validity, ensuring that it has not been contaminated or destroyed by bad sampling or transfer techniques.

Compositional research of reservoir fluid is a major component of a PVT analysis and has several applications in reservoir and production engineering. The most important application is establishing how much gasoline, kerosene, fuel oil and bitumen will be extracted when refining a barrel of crude oil. Another application is detecting corrosive components that require special consideration when selecting production and transportation equipment. Composition is also required as an input to equation-of-state simulators used for reservoir description. [18]

There are several different techniques used to determine the sampled fluid composition. Those can vary depending on the sampling procedure, however gas chromatography, distillation, and mass spectrometry are always used, as described in the two flowcharts that can be found in appendix A. For this project the surface samples were directly analyzed in the GC, instead the bottomhole samples were flashed to do a gas detection run and subsequently was calculated a recombined gas composition.

Flashed gas concentration is obtained analyzing the gas coming from the oil when pressure is bellow bubble point pressure, as demonstrated in figure 22. Recombined gas concentration is the one more similar to the actual reservoir fluid composition. This concentration is obtained mixing the two phases together in the same proportion in which they were produced.

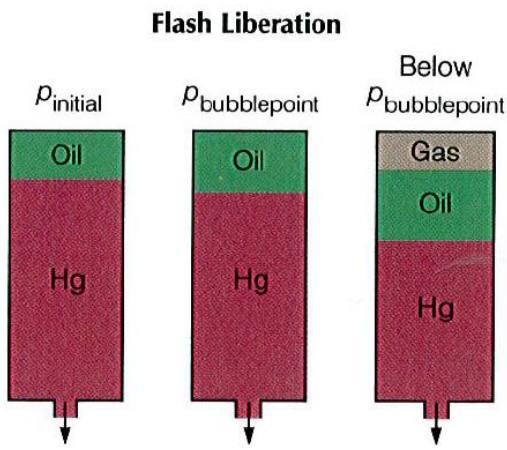


Figure 22 – Flashed gas procedure. [17]

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3

Data Quality Control

Contents

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3.1. Pre-analysis of the data

As outlined before the datasets used on this project are from eight different wells. To protect the data confidentiality the wells were named well 1, well 2, and so on. For each well was available one gas log, recorded during the drilling operation, and one PVT report, which was the result of the downhole tests made after the well has been drilled.

The pre-analysis stage consists in identifying and highlighting the data collection techniques used to gather the surface and subsurface information for each well. The next tables summarize the data collection techniques for each well.

Table 3 – Pre-analysis summary for mud gas data.

Gas Extraction	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8
QGM	No	No	No	Backup	No	No	No	No
CVD	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Heater	Yes	Yes	No	No	No	No	No	Yes
DeltaGas	Yes	No	No	No	No	No	No	No
Gas Detection								
DualFID	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
DualFID Star	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Gas Data Treatment								
Raw data	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
EEC	No	No	No	No	No	No	No	No
Delta Gas System	Yes	No	No	No	No	No	No	No
Mud Type								
WBM	Yes	No	No	No	No	No	Yes	No
OBM	No	Yes	Yes	Yes	Yes	Yes	No	Yes

After a quick analysis of table 3 it is possible to notice that in all the wells the used gas trap was the constant volume degasser (CVD). Additional features to the gas extraction system, as the mud heater, were used only in three wells, and the delta gas extraction configuration was used only in well number 1.

As previously mentioned, the basic gas detection service includes only the DualFID chromatograph, which analyzes gas species from methane to pentane. Therefore, all the wells have this sort of chromatography and only some wells have advanced gas analysis using the DualFID Star chromatograph.

For this project it will be only used raw gas data until pentane, once it is desired to have a common starting point for further studies. The details about the mud type give important information because it is expected different types of interaction with the gas components depending on the mud chemical composition and temperature.

Table 4 – Pre-analysis summary for downhole fluid data.

Sample type	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8
Bottomhole - DST	Yes	Yes	No	No	No	No	No	Yes
Bottomhole - MDT	No	No	Yes	No	No	Yes	Yes	Yes
Surface Separator	Yes	Yes	No	Yes	Yes	No	No	No
Sample from								
Same well	No	No	Yes	No	Yes	Yes	Yes	No
Adjacent well	Yes	Yes	No	Yes	No	No	No	Yes
Analyze technique								
Flashed gas	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Recombined fluid	Yes	Yes	No	No	No	Yes	Yes	Yes
Simple GC	Yes	Yes	No	Yes	Yes	No	No	No

Regarding the table 4 it is important to observe that each well is a specific case and it is difficult to gather common characteristics in order to do a proper comparison. Nevertheless, for the development of this project it was taken into account downhole fluid samples from the same or adjacent wells in order to compare with mud gas data.

In these datasets the downhole fluids were collected under different conditions. For some wells the sample was taken at the surface separator, and in other wells the fluid collection occurred at the bottom of the hole through an MDT or DST.

Different techniques were applied in the laboratories to obtain the molecular composition of the samples. The simple gas chromatography was run in the samples collected at the surface separator. In the other hand, the samples collected trough a DST or MDT were flashed to do a gas detection run (BHS FG) and subsequently a recombined gas composition (BHS RG) was calculated, in order to reach an approximation of the real reservoir fluid concentration.

3.2. Quality control of gas data

Ensure gas data quality is one of the most important steps to achieve meaningful results. It is important to mention that not all the gas datasets used in this project had enough information to do a proper quality control test. However, the gas logs received had been already under the quality control assessment of the mud logging company, therefore were considered as good quality data. Nevertheless, when enough information was available within the dataset, a quality control check was done in order to identify characteristics and attributes of the data.

One additional gas detector, named total gas, is always installed to cross check the information coming from the gas chromatographs. This device is a simple flame ionization detector that utilizes a flame produced by the combustion of hydrogen and air. When an organic compound enters the flame it is burnt and then a very small part is ionized, which results in the production of electrons and positive ions. The stream of free electrons is directed to a measuring circuit inside the detector. The measurement circuit senses the electron stream as a current that is proportional to the amount of organic matter in the flame.

In this way it is possible to compare the gas analysis arriving from the gas chromatograph with the one coming from the total gas detector. This cross checking method consists in a gas quality ratio (GQR) between the results from both instruments. The equation 7 shows the ratio applied when analyzing gas components up to pentane. The same principle is used when performing a cross checking operation for heavy gases.

$$GQR = \frac{Total\ Gas}{C_1 + 2 \times C_2 + 3 \times C_3 + 4 \times (nC_4 + iC_4) + 5 \times (nC_5 + iC_5)} \tag{7}$$

Good gas quality data will have a GQR between 0,8 and 1,2, as illustrated in figure 23. If the ratio result is out of this range that means unreliable gas data for that specific depth. There are many reasons for poor quality data, the main problems are related with gas detectors incorrect calibration or with contamination within the gas samples.

Another possible problem is when gas samples have components heavier than pentane. The basic gas chromatograph analyzes components until pentane, on the other hand the result from the total gas detector considers all the organic matter in the sample once the instrument does not have any separation column. Consequently the ratio is not valid anymore once detectors are considering different ranges of components.

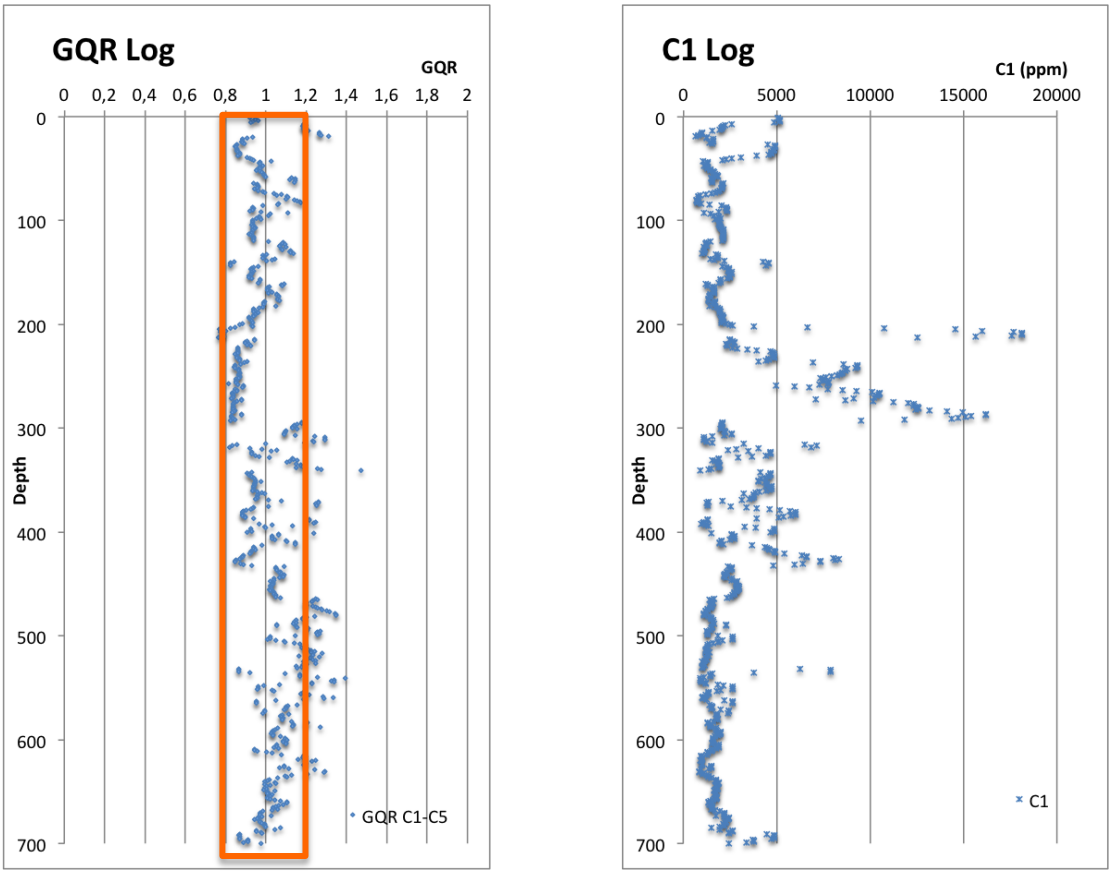

Figure 23 – GQR chart alongside with methane concentration chart for well 1.

A quality control test was performed for well 1 using the equation number 7. It is crucial to plot the gas quality ratio alongside with the absolute value of methane, as showed in the figure 25. In this way, any drop of GQR due to low amount of gas will be identified. As a rule of thumb, when methane concentration is below 100 ppm if the GQR goes out of the desired window is because the total gas instrument is approaching its accuracy limit.

In the case of well 1 it is possible to check that GQR values are inside of the acceptable range. The well section represented in the figure 23 corresponds to the reservoir interval. The low gas readings at surface mean the well was drilled in overbalanced conditions. The gas readings above the background gas level are only due to the liberated gas, therefore it is easy to estimate where are the producing intervals in this log.

The figure 24 shows the GQR log alongside with the methane concentration for well number 2. For this well the GQR was calculated using components from methane to pentane. Analyzing the GQR log it is possible to visualize the perfect behavior of the ratio inside the desired interval, which means reliable gas data for that specific depth interval of well 2.

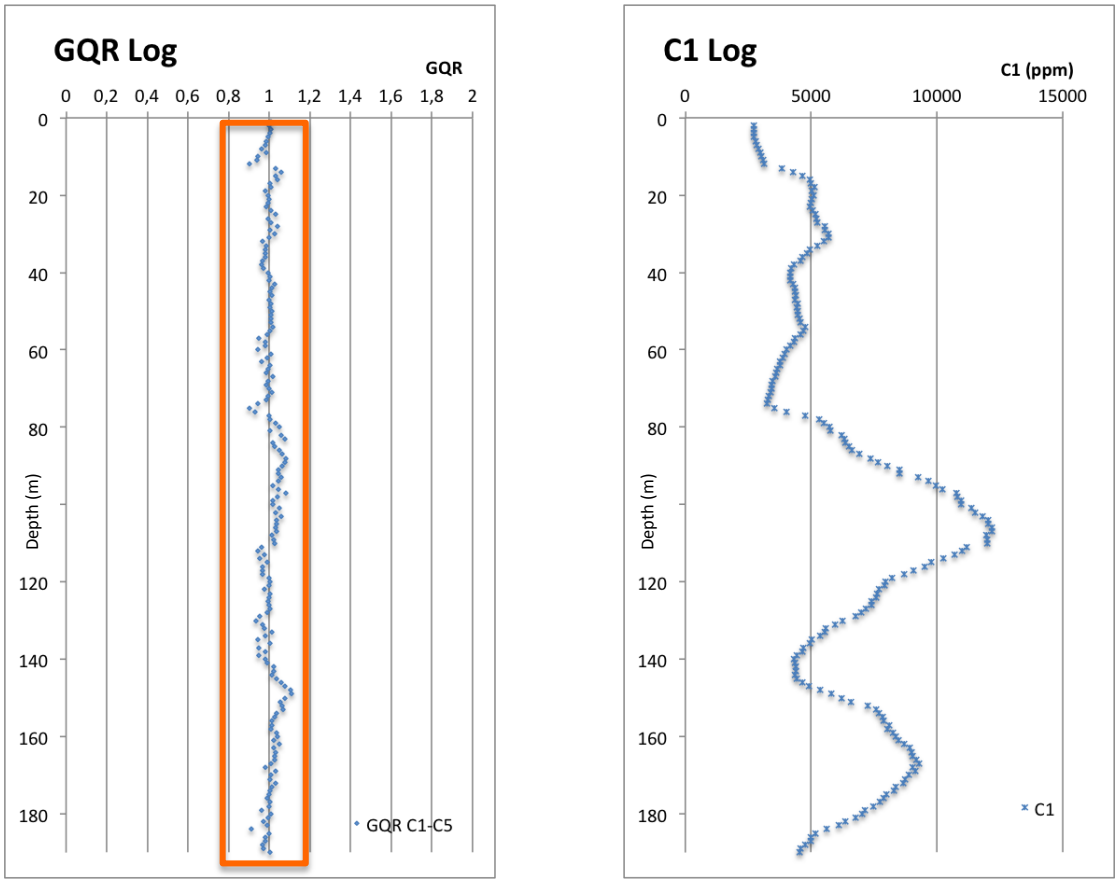

Figure 24 – GQR chart alongside with methane concentration chart for well 2.

The quality control for well number 3 is presented in figure 25. For this well it was possible to compute the quality ratio using gas components until heptane. For comparison proposes it was decided to calculate two different gas quality ratios, one using components from methane to pentane, and a second ratio using gas components until heptane.

In the figure 25 is possible to check the poor values of GQR and the wrong behavior of the trend when considering only gas components until pentane. In this way the heavier components were ignored, and, when their concentration was significant, the ratio goes out of the desired interval. In the other hand, when GQR takes into account gas components until heptane the trend fits perfectly inside of the desired interval.

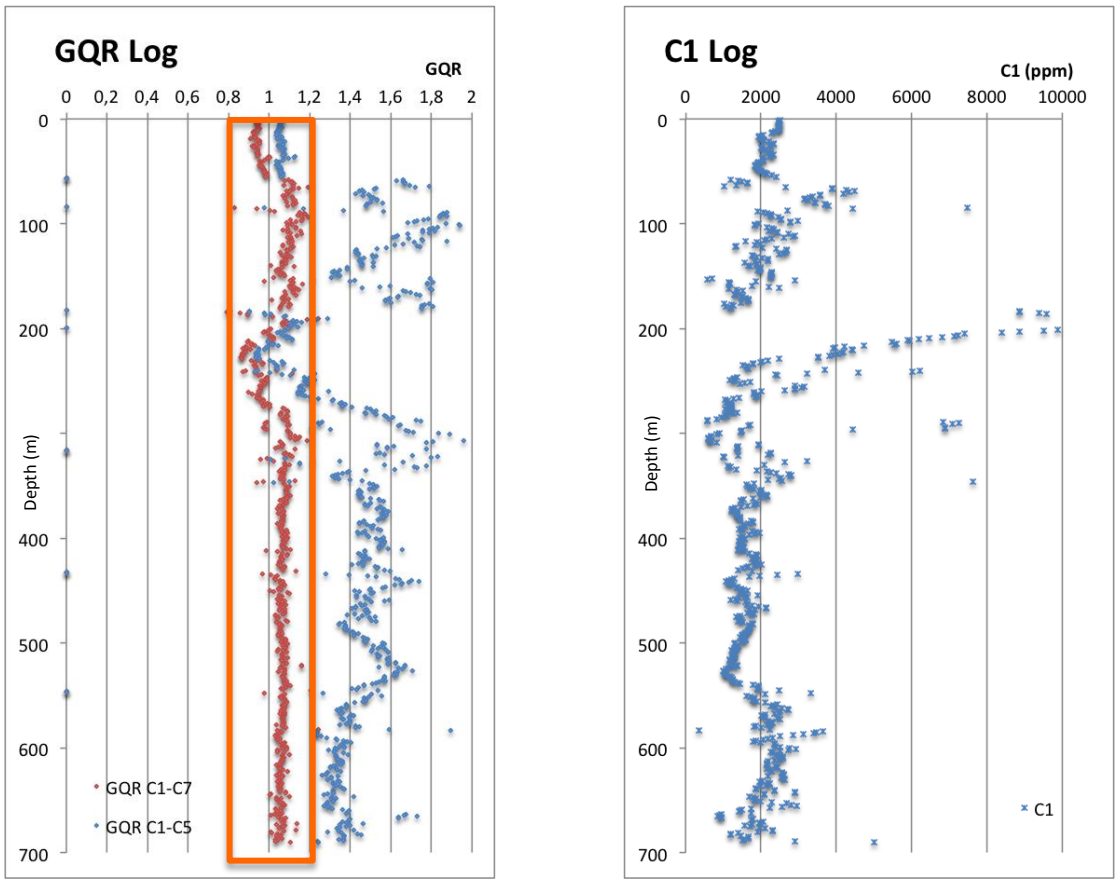

Figure 25 – GQR chart alongside with methane concentration chart for well 3.

Another interesting detail can be analyzed in figure 25, when methane concentration has a peak the GQR (C_1-C_5) fits inside the desired interval. This fact occurs because the concentration of heavier components becomes relatively smaller compared to the amount of lighter gases, therefore the ratio will become closer to one.

3.3. Quality control of gas equipment data

The quality control of the mud gas data was not only performed to the gas itself but also to the surface gas system. One standard principle to ensure meaningful data is the constant physical extraction conditions. In this way, when enough information was available, a quality control check was performed to the surface gas equipment.

In the figure 26 it is possible to check on the left side the usual GQR and the GQR heavy, which takes into account the heavier components in the gas. The CVD flow rate is the flow of the feeding stream to the degasser and should be a stable value around 4 liters per minute. The GDS flow rate is the flow inside the gas line from the degasser to the gas distribution system. This flow is guaranteed using a vacuum pump and it should be a kept around 4 liters per minute.

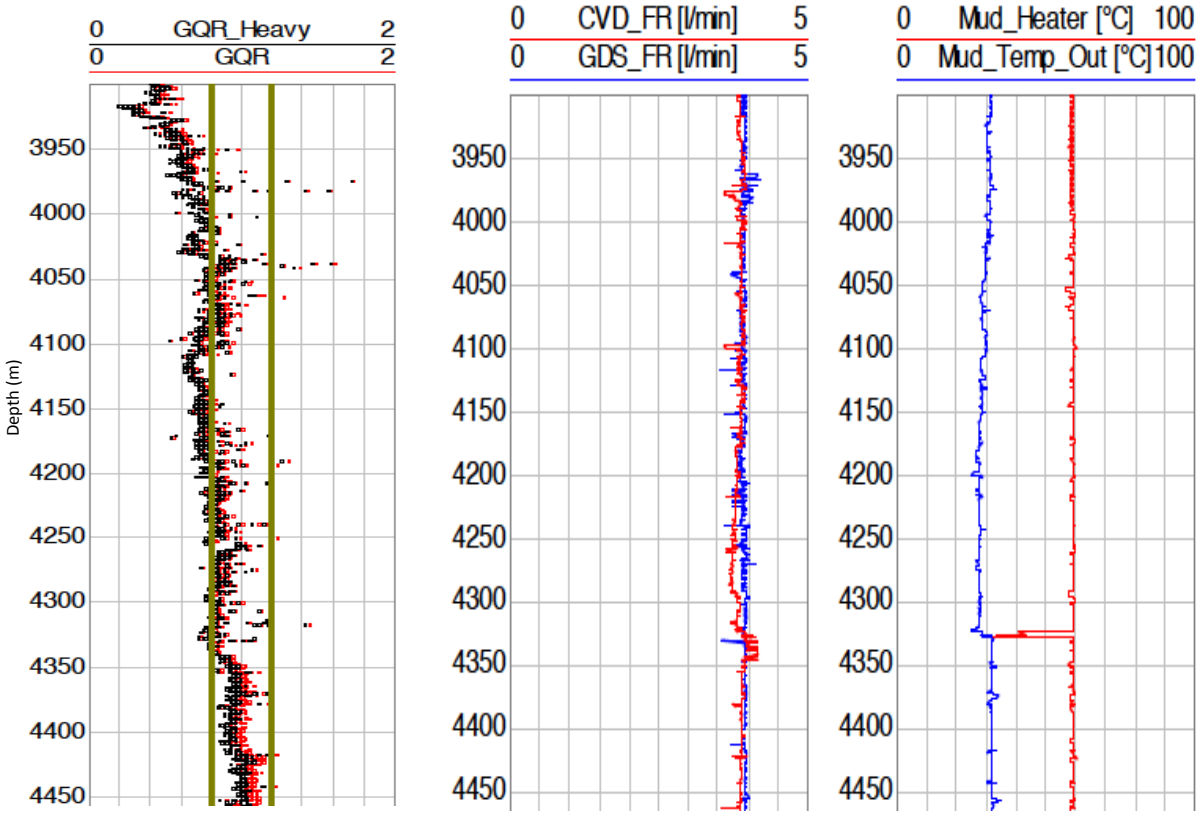

Figure 26 – Quality control charts for gas data and gas equipment data for this section of the well, courtesy of Geolog.

The information's about the mud heater are the mud temperatures when the mud returns from the well, and when the mud comes out from the heating system. In this way it is possible to ensure a constant mud feeding temperature from the mud heater to the degasser.

The mud heating system is a key component of the puzzle to ensure good gas quality data. It is known that the degassing efficiency of gas components within the mud varies with the temperature, therefore a constant mud feeding temperature is a must.

3.4. Quality control of downhole fluid data

When analyzing a PVT report it is important to understand the general information about the sampling methods, the tests performed, and how the results are presented. Since one of the goals of this project is to compare the downhole fluid composition with the surface gas readings, the compositional information in the PVT reports was evaluated and extracted for all the wells.

In the next chapter the downhole fluid composition for each well will be presented. It is important to understand that analyses were made in bottomhole samples and surface samples of downhole fluid. Consequently compositional results can be different for the same well at the same depth.

4

Data Treatment and Comparison

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This chapter is essentially a data mining approach to the datasets allowing a clear vision of the data behavior. The interpretation of the information presented in this section of the report, supports the model developed in chapter 5.

This chapter is segmented in four different topics. Firstly it was performed the surface and subsurface data treatment in order to have comparable information for the subsequent steps. The second stage was the comparison of the different samples. For each well, when available (check table 3 and 4), mud gas concentration and downhole fluid composition, both flashed and recombined gas analysis, was plotted.

The next step was the introduction of the extraction efficiency coefficient in the raw mud gas data, in order to take into account the total amount of gas in the mud. New comparisons of the datasets were made to understand the effect of that corrective factor. To conclude this chapter an uncertainty evaluation study was performed to understand the correlation between the data.

4.1. Downhole fluid data treatment

The bottomhole fluid composition for each well was extracted from the PVT reports. The compositional information, expressed in terms of molar percent, considers the whole spectrum of analyzed hydrocarbons (from C_1 to $^{+}C_{27}$). This information is presented in table 5.

After a careful assessment of the pre-analysis study (table 3), it is possible to infer that only two datasets have all the correct features to enable a proper heavy gas analysis. Due to this detail, as previously mentioned, this project will only take into consideration gas data until pentane.

Once the comparison with mud gas will be carried out using a range from methane to pentane, the next step is to recalculate the downhole fluid molar percentages of the analyzed species. The new values were obtained applying equation number 8 to the previous data (table 5), and can be checked in table 6.

$$Percentage = \frac{C_i}{\sum_{i=1}^{5} C_i} \tag{8}$$

Table 5 – Downhole fluid composition for all the tests.

	Well 1			Well 2			Well 3	Well 4	Well 5
	Surface sample	**Bottomhole sample**		**Surface sample**	**Bottomhole sample**		**Bottomhole sample**	**Surface sample**	**Surface sample**
(Mol %)	GC	FG	RG	GC	FG	RG	FG	GC	GC
C_1	74,76	59,96	68,55	81,58	77,35	51,48	68,55	90,69	83,03
C_2	13,11	13,82	15,12	8,80	10,33	6,95	15,12	4,25	6,76
C_3	6,84	11,14	7,87	3,48	4,98	3,86	7,86	1,63	3,19
iC_4	0,91	2,47	0,90	0,41	0,64	0,71	0,89	0,37	0,42
nC_4	1,31	4,73	2,44	0,73	1,21	1,76	2,44	0,47	0,96
iC_5	0,30	1,82	0,43	0,15	0,27	0,81	0,43	0,17	0,25
nC_5	0,23	1,57	0,46	0,13	0,24	0,93	0,46	0,12	0,32

	Well 6		Well 7		Well 8 – Depth 1		Well 8 – Depth 2		Well 8 – Depth 3	
	Bottomhole sample		**Bottomhole sample**		**Bottomhole sample**		**Bottomhole sample**		**Bottomhole sample**	
(Mol %)	FG	RG	FG	RG	FG	RG	FG	RG	FG	RG
C_1	47,98	5,80	28,64	4,20	76,95	17,66	83,44	20,07	73,37	12,93
C_2	12,86	1,68	18,78	2,95	5,88	1,40	2,30	0,61	5,69	1,06
C_3	19,64	3,41	24,12	4,57	7,75	2,17	4,69	1,33	8,98	1,93
iC_4	3,25	0,83	3,45	0,87	2,11	0,83	2,11	0,74	2,74	0,77
nC_4	7,84	2,37	11,10	3,52	3,41	1,65	3,12	1,30	4,38	1,45
iC_5	2,30	1,34	2,95	1,74	1,05	0,96	1,16	0,79	1,38	0,85
nC_5	2,59	1,86	3,97	3,00	1,08	1,22	1,18	1,01	1,34	1,86

Table 6 – Recalculated downhole fluid composition for all the tests.

	Well 1			Well 2			Well 3	Well 4	Well 5
	Surface sample	**Bottomhole sample**		**Surface sample**	**Bottomhole sample**		**Bottomhole sample**	**Surface sample**	**Surface sample**
(%)	GC	FG	RG	GC	FG	RG	FG	GC	GC
C_1	76,71	62,78	59,95	85,62	81,40	77,41	71,58	92,80	87,46
C_2	13,45	14,47	14,02	9,24	10,87	10,45	15,79	4,35	7,12
C_3	7,02	11,66	11,79	3,65	5,24	5,80	8,22	1,67	3,36
iC_4	0,93	2,59	2,85	0,43	0,67	1,07	0,94	0,39	0,44
nC_4	1,34	4,95	5,77	0,77	1,27	2,65	2,55	0,49	1,01
iC_5	0,31	1,91	2,88	0,16	0,28	1,22	0,45	0,18	0,26
nC_5	0,24	1,64	2,74	0,14	0,25	1,40	0,48	0,13	0,34

	Well 6		Well 7		Well 8 – Depth 1		Well 8 – Depth 2		Well 8 – Depth 3	
	Bottomhole sample		**Bottomhole sample**		**Bottomhole sample**		**Bottomhole sample**		**Bottomhole sample**	
(%)	FG	RG	FG	RG	FG	RG	FG	RG	FG	RG
C_1	49,74	33,55	30,79	20,14	78,33	68,24	85,14	77,62	74,94	62,04
C_2	13,33	9,72	20,19	14,15	5,99	5,40	2,35	2,36	5,82	5,07
C_3	20,36	19,72	25,93	21,92	7,88	8,3%	4,78	5,15	9,18	9,26
iC_4	3,37	4,80	3,71	4,17	2,16	3,19	2,16	2,88	2,81	3,69
nC_4	8,13	13,71	11,93	16,88	3,47	6,36	3,18	5,04	4,47	6,97
iC_5	2,38	7,75	3,17	8,35	1,07	3,71	1,18	3,07	1,41	4,06
nC_5	2,69	10,76	4,27	14,39	1,10	4,72	1,21	3,89	1,38	8,91

4.2. Gas peaks identification and treatment

In this project we are analyzing two different fluids (mud gas and downhole fluid) both tied to a certain depth scale. It is important to refer that mud gas data is linked with the driller's depth from the rotary table, in the other hand downhole fluid data is associated with well test independent depth. In some cases these depths can be different in a couple of meters; therefore close attention should be paid when comparing data from these two different types of datasets.

The first objective consisted in identifying the gas peak associated to the depth of the downhole test. It seems simple, however some thumb rules should be followed. Before any kind of further investigation, it is essential the basic understanding of each well design in order to know if it is a horizontal well, a side-track well, et cetera.

The gas data in the interval associated to the sampling depth of the downhole test should be plotted in order to identify the gas peaks within that interval. Once plotted different situations can occur:

1. One gas peak – If all the previous steps were correctly done this gas show should match the downhole fluid sample and have a similar behavior under the formation evaluation tools.
2. One or more gas peaks – In this case two different approaches should be executed. If both gas shows are clearly representative then an average of the peaks should be made in order to mimic the producing conditions of two productive layers during well testing. If one peak is much bigger than the other then only that peak should be taken into account, because Gas While Drilling principle says that the larger a liberated gas show is, the more representative it is of the real formation fluid composition.
3. No gas peaks – In this case, probably, the previous steps (pre-analyze of the datasets, the sampling depth of the downhole tests, or the understanding of well design) were not correctly performed.

The figure 27 shows the aforementioned procedure for well 3. In this case two peaks can be observed, the first peak has almost the double of gas concentration compared with the second one. Consequently, the first gas show was chosen for the comparison with the downhole fluid. The same process was followed for the gas peak selection associated to each downhole sample.

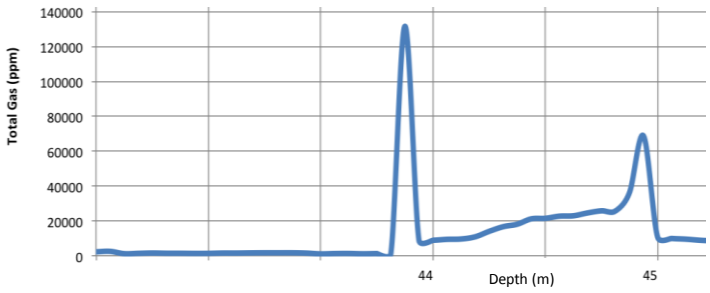

Figure 27 – Gas peak associated to the downhole fluid sampling depth.

The gas peak composition for each well is presented in table 7. To allow a proper comparison with downhole fluid data, the mud gas concentration in parts per million (PPM) was transformed in percentage values. These new values were obtained applying equation number 8, and can be observed on table 8.

Table 7 – Mud gas composition in PPM for all the samples.

(PPM)	**Well 1**	**Well 2**	**Well 3**	**Well 4**	**Well 5**	**Well 6**	**Well 7**	**Well 8 - Depth 1**	**Well 8 - Depth 2**	**Well 8 - Depth 3**
C_1	17571	8687	131616	24264	7425	2026	4384	12875	38988	18185
C_2	1984	842	24554	1099	827	394	1839	552	908	584
C_3	1356	285	11288	349	492	428	2254	625	1083	658
iC_4	225	25	562	21	55	47	247	42	42	100
nC_4	183	67	2069	107	183	142	994	457	1057	542
iC_5	467	19	297	19	57	58	346	260	440	300
nC_5	173	18	245	36	81	77	518	300	220	300

Table 8– Mud gas composition in percentage for all the samples.

(%)	**Well 1**	**Well 2**	**Well 3**	**Well 4**	**Well 5**	**Well 6**	**Well 7**	**Well 8 - Depth 1**	**Well 8 - Depth 2**	**Well 8 - Depth 3**
C_1	80,02	87,37	77,13	93,70	81,41	63,87	41,43	85,20	91,22	87,98
C_2	9,04	8,47	14,39	4,24	9,07	12,42	17,38	3,65	2,12	2,83
C_3	6,18	2,87	6,62	1,35	5,39	13,49	21,30	4,14	2,53	3,18
iC_4	1,02	0,25	0,33	0,08	0,60	1,48	2,33	0,28	0,10	0,48
nC_4	0,83	0,67	1,21	0,41	2,01	4,48	9,39	3,02	2,47	2,63
iC_5	2,13	0,19	0,17	0,07	0,63	1,83	3,27	1,72	1,03	1,45
nC_5	0,79	0,18	0,14	0,14	0,89	2,43	4,90	1,99	0,51	1,45

4.3. Mud gas Vs. Downhole fluid

At this point the gas peaks associated to the downhole fluid samples are identified and characterized. The next step is the comparison of this information in order to assess the uncertainty associated to the data.

The first target when comparing these two different types of information will be the validation of the selected gas show to the correspondent downhole fluid sample. To do that it will be used the two previously introduced formation evaluation tools, the Pixler plot and $\frac{Ci}{\sum Ci}$ ratio, in order to understand if both fluids have the same origin.

It is important to remember that for each downhole fluid sample there is only one associated gas show. However the same gas peak will be compared with different compositions obtained from the different laboratory test performed on the bottomhole fluid sample.

The numerical values and comparison charts made for all the samples can be found in appendix B and C. Nonetheless taking some of the wells as examples for analysis, it is possible to observe that mud gas has almost a perfect compositional match with downhole fluid collected at surface, as compared in figure 28 and 29. Examining the conditions of each sample collection it is simple to explain this fact since both samples were collected at analogous conditions.

When observing the compositional match between downhole samples and mud gas, it is clear the existence of large discrepancies, which can be explained due to the different sampling conditions. The bottomhole sample is collected near reservoir conditions, on the other hand the gas shows are extracted and analyzed at surface conditions. Nevertheless, the Pixler plot confirms that mud gas compositional characteristic is similar to the reservoir fluid (BHS RG), confirming the same origin for the samples.

Comparing the compositional match between the gas show and the analyses from the bottomhole fluid sample, the best fit occurs with the flashed gas analysis. This happens because, as mentioned in chapter 2, the flashed gas analysis only take into account the gas part of sample, instead the recombined gas concentration is taking both gas and liquid components into consideration.

When analyzing the comparison between the downhole fluids collected at the surface separator and at the bottom of the well it is possible to notice wide divergences in the Pixler plot. These mismatches happen due to the different collection conditions of the samples, as mentioned in the above comparison case among mud gas data and downhole fluid samples.

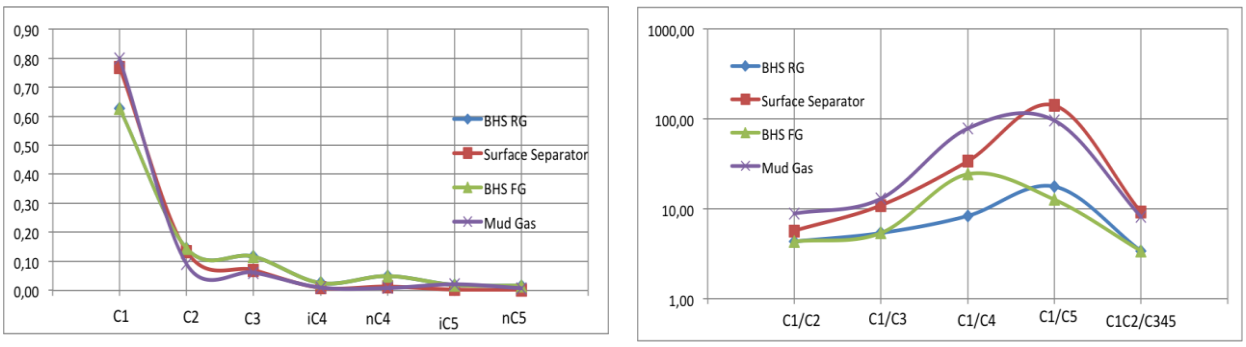

Figure 28 – Comparison of different data for well 1.

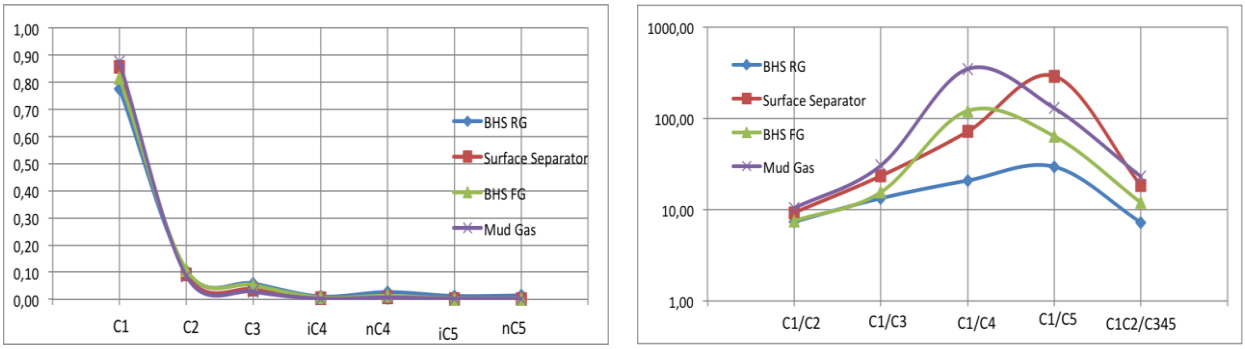

Figure 29 – Comparison of different data for well 2.

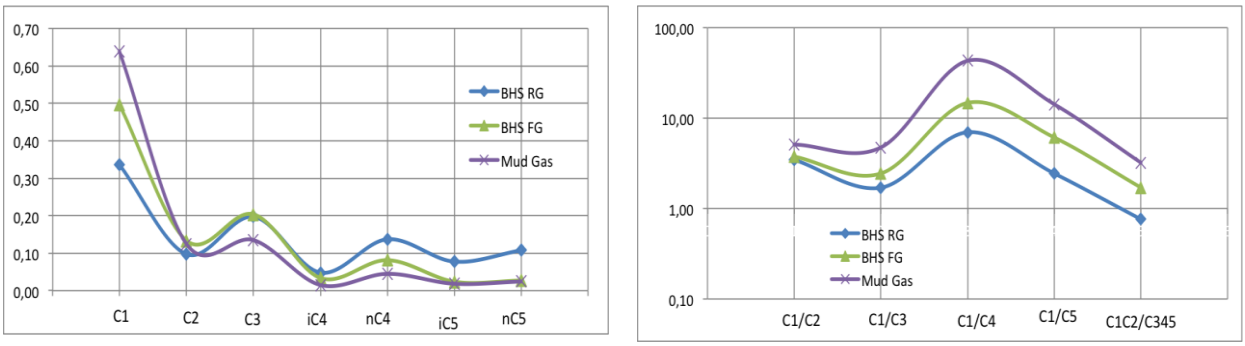

Figure 30 – Comparison of different data for well 6.

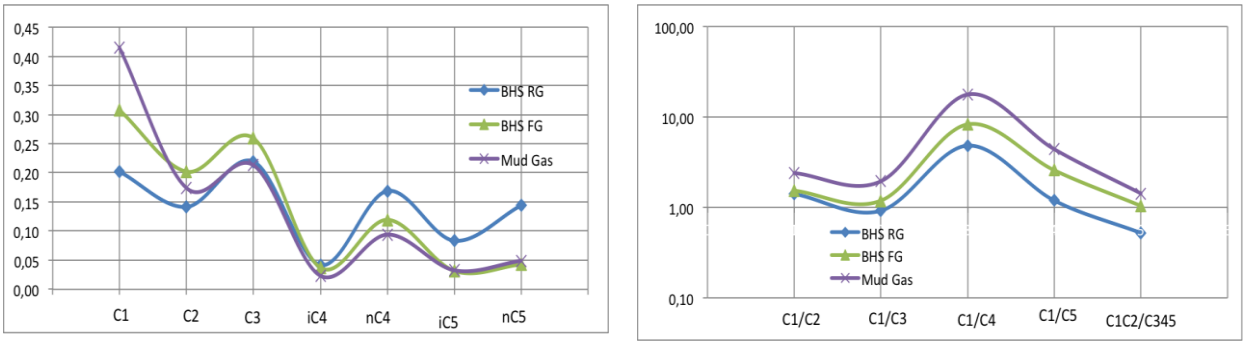

Figure 31 – Comparison of different data for well 7.

4.4. Mud gas data with extraction efficiency coefficient

As reviewed on the second chapter, the extraction efficiency coefficient is necessary because not all gas in the mud is extracted in the degassing process. Additionally, each molecule has different degassing efficiencies, commonly heavier gases are extracted less efficiently.

By applying the procedure to discover the extraction efficiency coefficients, in different wells around the world, Geolog found three different sets of EEC values, dependents on the mud properties, for each gas component. These approximations of extraction efficiency coefficients enable the correction of the gas shows composition value.

At this stage all the mud gas data (in PPM) was corrected with the appropriate EEC value. The coefficients used to calculate the corrected mud gas concentration were extracted from a EEC table that was kindly provided by Geolog. The final step was the recalculation of molar percentages, using equation 8, based on the corrected gas concentrations.

In the next charts it is possible to check the concentration and the Pixler plot behavior for the bottomhole sample flashed gas (BHS FG), the bottomhole sample recombined gas (BHS RG), the mud gas, and the mud gas corrected with the extraction efficiency coefficient. The information for all the wells can be found in appendix D.

For this project it is considered that BHS RG concentration is similar to the real reservoir fluid concentration, therefore our goal is to understand the dynamics between the corrected mud gas concentration and the BHS RG. These charts enable a quick comparison between the different samples and analysis techniques. When observing the Pixler plots it is clear that mud gas composition becomes much closer to the BHS RG composition after the extraction efficiency coefficients are applied.

In some cases the compositional match between mud gas with EEC and BHS RG is almost perfect, on the other hand for some samples the corrected mud gas composition is closer to the BHS FG composition. Nevertheless, it is safe to infer that mismatches in the Pixler Plot get worse when the gas component concentration becomes smaller. That is the reason why C_1/C_4, C_1/C_5 and $(C_1+C_2)/(C_3+C_4+C_5)$ have the large discrepancies when comparing mud gas EEC with BHS RG. These uncertainties will be studied in the next topic of this chapter.

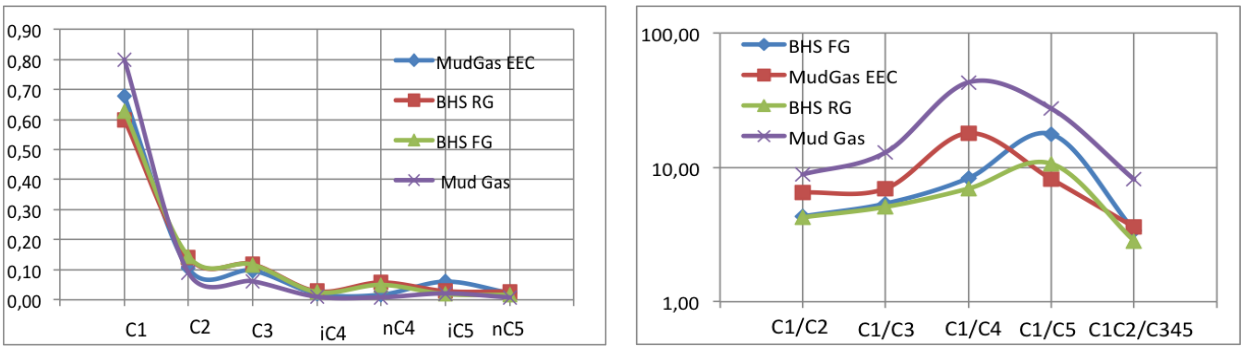

Figure 32 – Well 1 - Comparison between all the sample in the Pixler plot (right) and concentration plot (left).

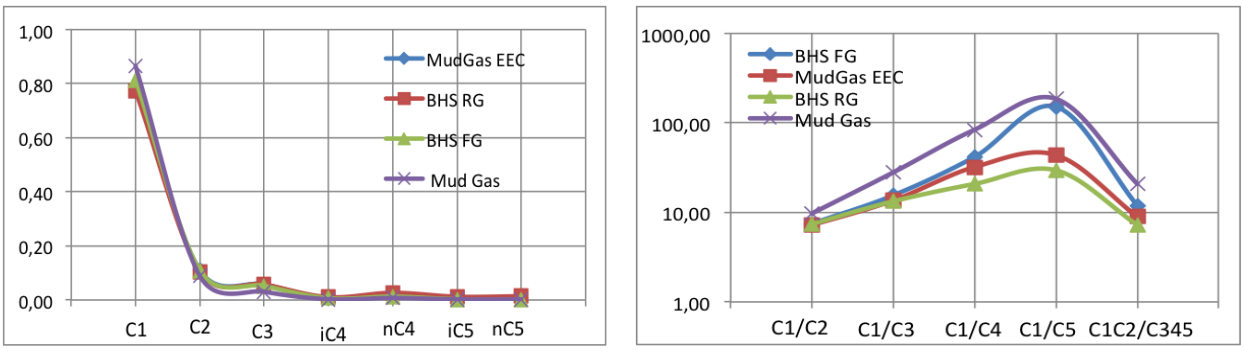

Figure 33 – Well 2 - Comparison between all the sample in the Pixler plot (right) and concentration plot (left).

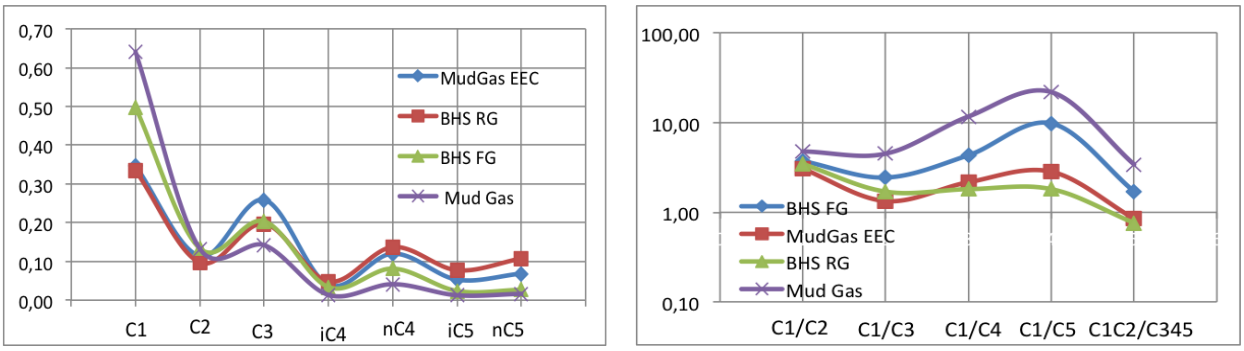

Figure 34 – Well 6 - Comparison between all the samples in the Pixler plot (right) and concentration plot (left).

4.5. Data analysis

The necessity of uncertainty evaluation comes as a comparison tool between the available data. The aim of this topic is the understanding of variables relationship, as well as, the study of the relative error comparisons among them. This study was applied to three different relations:

1. Mud gas EEC versus BHS FG;
2. Mud gas EEC versus BHS RG;
3. BHS FG versus BHS RG.

However before the error analysis it was decided to test the correlation between the data. The correlation coefficients were found using the equation 9.

$$Correlation\ (r) = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2]\,[n\sum y^2 - (\sum y)^2]}} \tag{9}$$

The correlation coefficients give an indication of the linearity of the data. A correlation coefficient of 1 or -1 implies respectively a perfect positive or negative linear correlation. If there is no linear correlation or a weak linear correlation the correlation coefficient will be close to zero.

In the tables 9 and 10 is possible to find the correlation coefficient for each component between the mud gas samples with EEC and, respectively, the bottomhole flashed gas samples and recombined gas samples. From the analysis of these tables it is possible to infer that mud gas data corrected with EEC has a stronger relationship with recombined gas samples than with flashed gas data. This can be easily explained considering the application purpose of the extraction efficiency coefficient. As previously explained, this coefficient is transforming the gas show extracted and analysed at surface into an approximation of the total amount of gas in the mud. The correlation between mud gas EEC and BHS RG becomes better because the calculated total amount of gas in the mud is an approximation of the real reservoir fluid.

Table 9 – Correlation between mud gas with EEC versus bottomhole flashed gas sample.

	C_1 Mud EEC	C_2 Mud EEC	C_3 Mud EEC	iC_4 Mud EEC	nC_4 Mud EEC	iC_5 Mud EEC	nC_5 Mud EEC
C_1 FG	0,95						
C_2 FG	-0,78	0,96					
C_3 FG	-0,98	0,73	0,96				
iC_4 FG	-0,78	0,27	0,74	0,76			
nC_4 FG	-0,94	0,62	0,90	0,87	0,85		
iC_5 FG	-0,89	0,56	0,86	0,87	0,77	0,68	
nC_5 FG	-0,92	0,60	0,88	0,84	0,85	0,61	0,76

Table 10 – Correlation between mud gas with EEC versus bottomhole recombined gas sample.

	C_1 Mud EEC	C_2 Mud EEC	C_3 Mud EEC	iC_4 Mud EEC	nC_4 Mud EEC	iC_5 Mud EEC	nC_5 Mud EEC
C_1 RG	0,98						
C_2 RG	-0,56	0,93					
C_3 RG	-0,98	0,72	0,97				
iC_4 RG	-0,75	0,12	0,72	0,71			
nC_4 RG	-0,97	0,57	0,94	0,88	0,93		
iC_5 RG	-0,95	0,47	0,92	0,86	0,95	0,59	
nC_5 RG	-0,85	0,38	0,80	0,75	0,91	0,54	0,84

When comparing in both tables the correlation factors for C_3, nC_4 and nC_5, it is possible to notice the decreasing trend of the correlation indicator with the increase in molecular weight. A feasible explanation for this fact can be the lower gas concentration associated to the heavier components, which will make them more susceptible to be masked due to errors or contaminations.

Another interesting information that can be drawn from these tables is the very different correlations between iso-molecules compared with normal-molecules, as the case of iC_4-nC_4 and iC_5-nC_5. Nonetheless the iso-butane has a bigger correlation factor than iso-pentane following the above conclusion.

To better understand these results it was decided to calculate the relative errors between the compared data. The errors were calculated applying equation number 10, and always considering the mud gas data as the measured variable. The results can be consulted in appendix E.

$$Relative\ error = \frac{|Measured\ value - Real\ value|}{Real\ value} \tag{10}$$

To clearly visualize and comprehend the results, the descriptive statistics of the errors were calculated, as well as, the information displayed in box-plots. The figures 35 and 36 present the two box-plots with the comparison between mud gas data EEC and, respectively, the bottomhole flashed gas sample and the recombined gas sample. Along with the box-plots it is possible to find the descriptive statistics in tables 11 and 12.

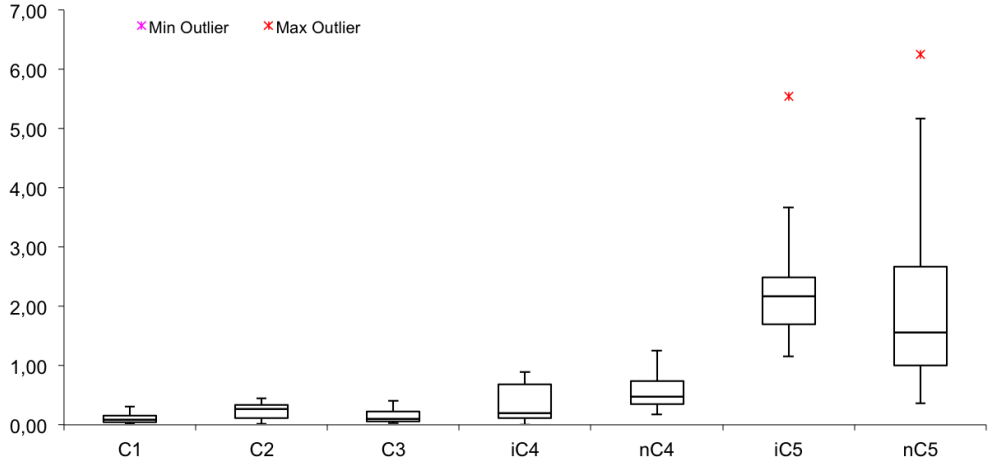

Figure 35 – Box plot of relative errors of mud gas EEC versus bottomhole flashed gas samples.

Table 11 – Descriptive statistics for relative errors of mud gas EEC versus bottomhole flashed gas samples.

	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5
Min	0,01	0,01	0,03	0,00	0,18	1,16	0,36
Q_1	0,04	0,12	0,06	0,12	0,35	1,70	1,00
Median	0,08	0,27	0,11	0,20	0,48	2,17	1,56
Q_3	0,16	0,34	0,22	0,69	0,73	2,48	2,67
Max	0,30	0,44	0,40	0,89	1,25	5,55	6,24
IQR	0,12	0,22	0,16	0,57	0,39	0,79	1,67
Upper Outliers	0	0	0	0	0	1	1
Lower Outliers	0	0	0	0	0	0	0

Comparing the information in both box-plots it is possible to take some conclusions. The common characteristics are the small range for errors in light gases (from C_1 to C_3) and the wider interval of error values when analysing butane and pentane fractions. The previous assumption that lower gas concentration associated to heavier components is making them more susceptible to be masked due to errors or contaminations, is also valid in this case.

Examining the box-plot in figure 38 it is valid to say that iso-molecules have a wider dissemination of errors than the normal molecules. This distribution of errors supports the above indication of lower correlation for iso-molecules than normal-molecules.

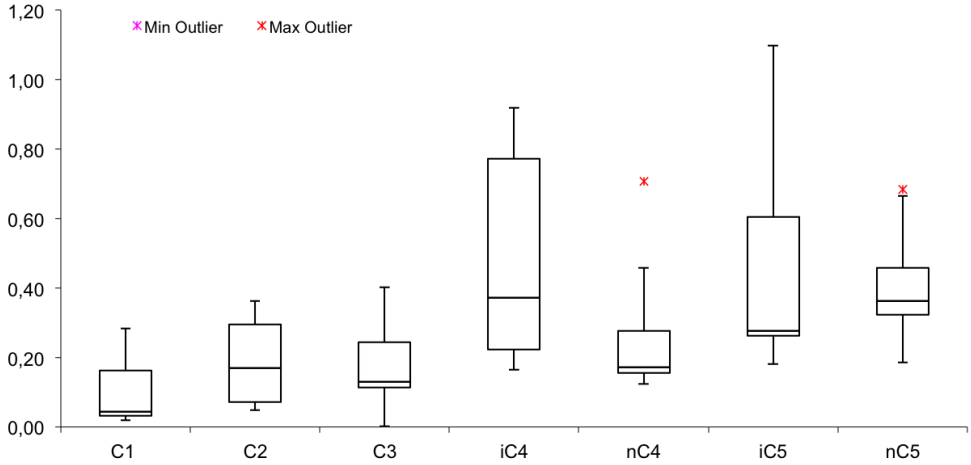

Figure 36 – Box plot of relative errors of mud gas EEC versus bottomhole recombined gas samples.

Table 12 – Descriptive statistics for relative errors of mud gas EEC versus bottomhole recombined gas samples.

	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5
Min	0,02	0,05	0,00	0,16	0,12	0,18	0,18
Q_1	0,03	0,07	0,11	0,22	0,15	0,26	0,32
Median	0,04	0,17	0,13	0,37	0,17	0,28	0,36
Q_3	0,16	0,30	0,24	0,77	0,28	0,61	0,46
Max	0,28	0,36	0,40	0,92	0,71	1,10	0,68
IQR	0,13	0,22	0,13	0,55	0,12	0,34	0,14
Upper Outliers	0	0	0	0	1	0	1
Lower Outliers	0	0	0	0	0	0	0

Analysing the statistic values of both box-plots it is clear that until propane the errors follow the same behaviour. However, that changes when facing butane and pentane fractions, the error intervals become wider in the flashed gas comparison than in the recombined gas comparison. To help the understanding of this phenomena a box-plot of relative errors between bottomhole flashed gas sample versus bottomhole recombined gas sample was made and can be found together with the descriptive statistic in figure 37 and table 13.

The box-plot of the relative errors between bottomhole flashed gas samples and bottomhole recombined gas samples was also made to demonstrate that even when both samples are collected under the same conditions and at the same time, there are always intrinsic differences associated to different analysis techniques.

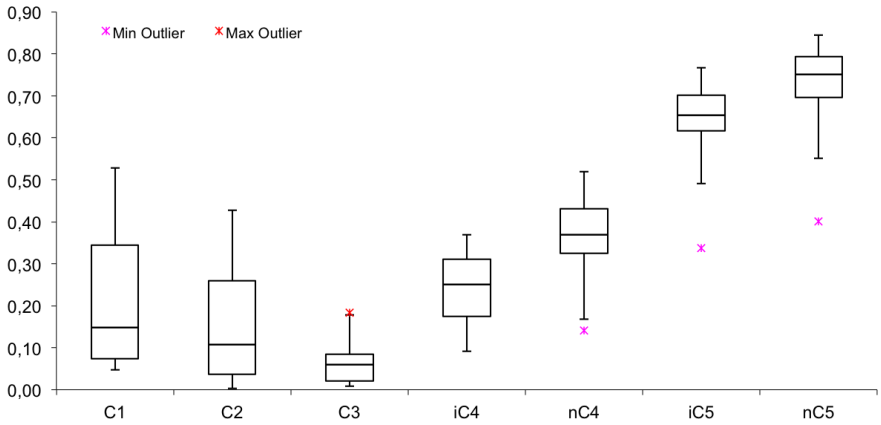

Figure 37 – Box plot of relative errors of BHS FG vs. BHS RG.

Table 13 – Descriptive statistics of relative errors of BHS FG and BHS RG.

	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5
Min	0,05	0,00	0,01	0,09	0,14	0,34	0,40
Q_1	0,07	0,04	0,02	0,18	0,33	0,62	0,70
Median	0,15	0,11	0,06	0,25	0,37	0,65	0,75
Q_3	0,35	0,26	0,08	0,31	0,43	0,70	0,79
Max	0,53	0,43	0,18	0,37	0,52	0,77	0,85
IQR	0,27	0,22	0,06	0,14	0,11	0,08	0,10
Upper Outliers	0	0	1	0	0	0	0
Lower Outliers	0	0	0	0	1	1	1

5

Linear Model

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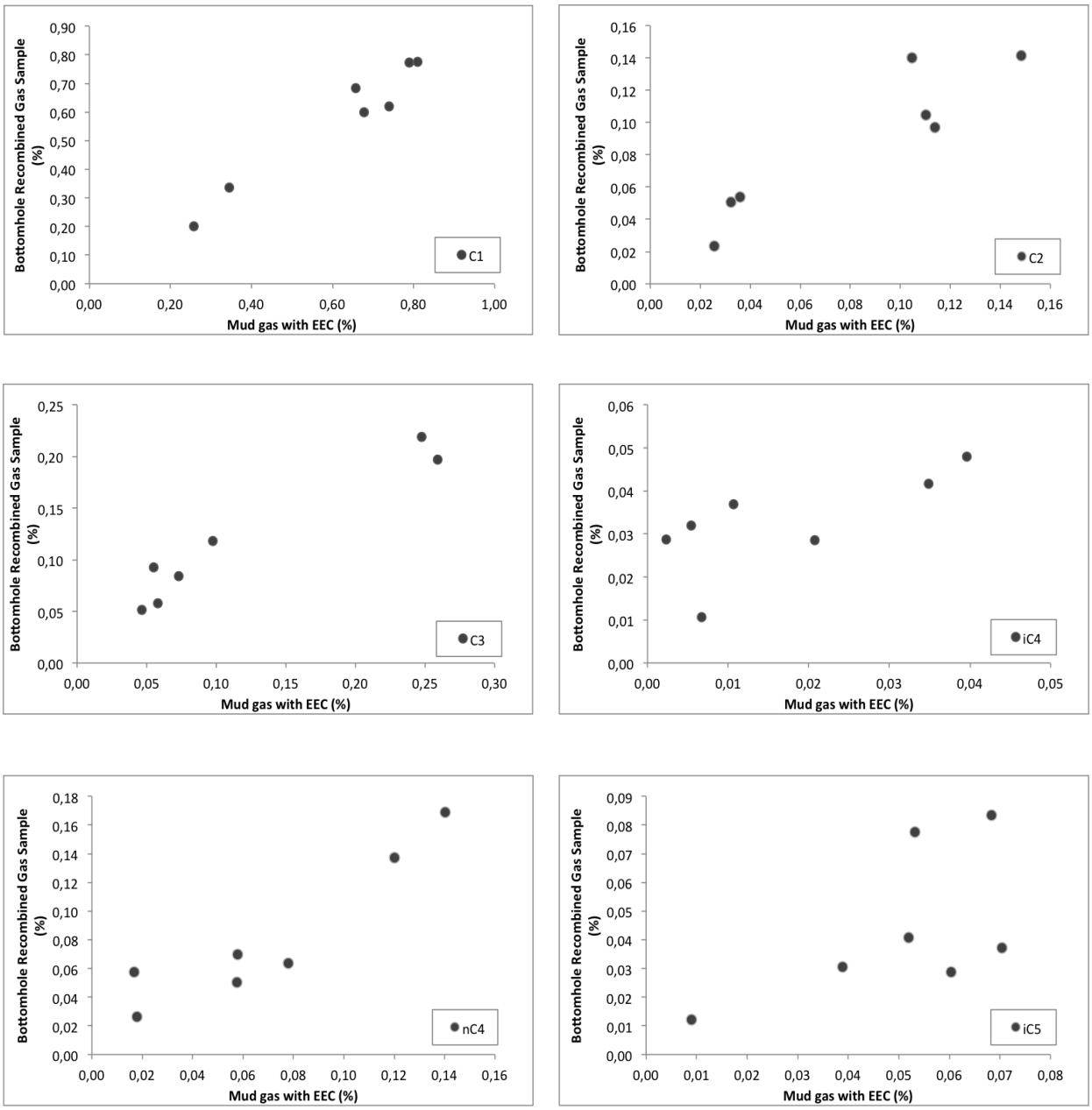
5.1. Model analysis 58

5.1. Model analysis

Since the objective of this project is to create a model able to predict, in real time, the reservoir fluid composition, further research is focussed only on the relationship between the corrected mud gas data and bottomhole recombined gas samples.

After the comparison and the uncertainty evaluation of the data, the next step is the development of a model to achieve the aforementioned goal. The first step was the representation of the bottomhole recombined gas sample versus the mud gas concentration corrected with the extraction efficiency coefficient. The plots for each component can be observed in figure 38.



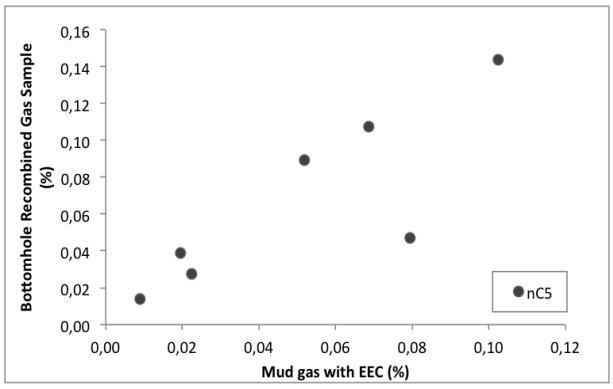


Figure 38 – Plot of corrected mud gas versus bottomhole recombined gas sample.

Observing the distribution of the points for each molecule, it was decided to test a linear regression fit. The linear regressions try to explain in different wells (i) the variation for each molecule on the bottomhole recombined gas composition (Yi) through the associated mud gas EEC composition value (Xi). The model is described in equation 11 below:

$$Y_i = mX_i + a + \varepsilon_i \tag{11}$$

Where m is the coefficient measuring the relationship between the recombined gas values and the corrected mud gas composition for each molecule, and ε_i is a random error term. In these regressions the constant (a) is zero once a null mud gas composition value implies a zero recombined gas concentration.

To estimate the model parameters it was used the least square method, which is a statistical procedure to fit the best model to the available data. With n observation pairs (Y_1, X_1), … , (Y_n, X_n), this estimation method gives the a and m values that minimizes the sum of the squared differences. This statistical method is explained in equation 12.

$$\sum_{i=1}^{n} {\varepsilon_i}^2 = \sum_{i=1}^{n} (y_i - a - mX_i) \tag{12}$$

The random error term is necessary to explain the differences between the observed value and the value given by the model. Therefore it quantifies how well the model can represent the observed data. There are four main assumptions that justify the use of linear regression model for prediction purposes:

1. Linearity of the relationship between the dependent and independent variables;
2. Statistical independence of the errors;
3. Homoscedasticity of the errors (constant variance);
4. Normality of the error distribution.

It is important to stress that these regressions only have seven pairs of data. Therefore, the added value of this project is the developed procedure and the qualitative indication of the relationship between the corrected mud gas and the BHS RG. The quantitative output is not reliable since the amount of available data is not enough do a proper statistical study. Nevertheless, the regressions details are present in table 14.

Table 14 – Summary of regression details for each component.

	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5
m coefficient	0,937	1,023	0,882	1,364	1,128	0,863	1,271
Standard error of m	0,0286	0,0786	0,0701	0,2992	0,0932	0,1498	0,1678
t-stat	32,70	13,01	12,59	4,56	12,11	5,76	7,58
P-value	5,34E-08	1,28E-05	1,53E-05	3,85E-03	1,93E-05	1,19E-03	2,75E-04
R^2	0,994	0,966	0,964	0,776	0,961	0,847	0,905

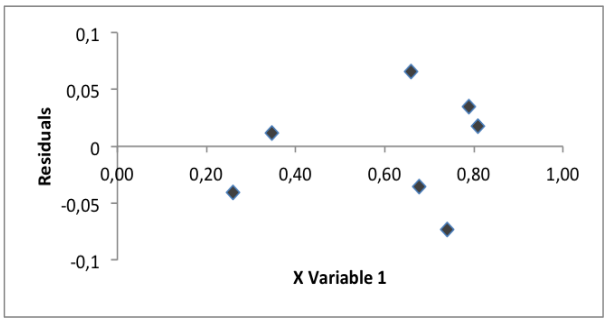
The first process when analyzing the data is called hypothesis testing, to determine the statistical significance of these results by rejecting the null hypothesis. The t-stat value is the ratio between the estimated values m, and its standard error. The P-value is the probability of observing a test statistic as extreme as the previously calculated value, assuming the null hypothesis is true. If the P-value is less than the significance level, we reject the null hypothesis. The significance level is dependent of the confidence interval for the regression.

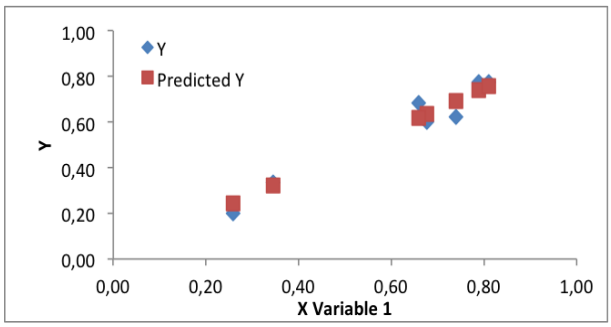
The proposed regressions have a confidence interval of 95%. Therefore, if P-values are lower than 0,05 the null hypothesis is rejected, proving the statistical validation of this model. Observing the P-values on table 14 is possible to confirm the statistical significance of all the proposed regressions.

The R^2 is the coefficient of determination, and gives information about the quality of the model to represent the desired variable. Taking methane as an example, the R^2 of 0,994 means that 99.4% of the variation on the bottomhole recombined gas is explained by the corrected mud gas values. Analysing the R^2 values it is safe to say that the model is robust to estimate the majority of the components, having a lower predictability power associated to iso-butane and iso-pentane molecules.

The residual and the line fit plot were used to confirm the four main assumptions that justify the use of a linear regression for prediction purposes. The plots for methane and iso-butane can be observed in figure 39, and, the plots for all the other components can be consulted in appendix F. The residual points for all the components appear to have a random pattern around the horizontal axis, being symmetrically distributed above and bellow the zero line, indicating a good fit for the linear model.

Observing the iso-butane plot is possible to notice three points with high positive residual value. It is important to stress that these three abnormal points belong to three different depth analysis from the same well. Therefore, these gas shows were analyzed by the same gas chain, under similar conditions and errors.





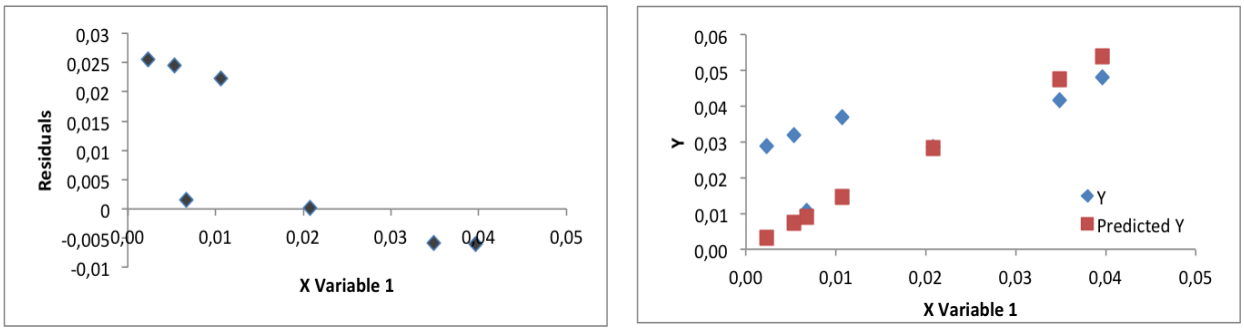


Figure 39 – Residual plot (left) and Line fit plot (right) for methane (above) and iso-butane (bellow) regression.

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Conclusions and recommendations for future research

The most important conclusions were drawn along with the results from the suggested methodology. Nevertheless it is relevant to review the main assumptions for this work procedure, in order to fully understand the initial starting point and the final goal of this project.

Due to the lack of information and the heterogeneity of the mud gas datasets it was impossible to extend this project research until the heavy gas components (C_6 - C_8). It was only take into consideration gas components until pentane. Another significant detail is the challenging task of obtaining from the oil companies the downhole fluid datasets for the same well that was logged at surface.

An additional relevant fact is the inexistence of extraction efficiency coefficients for all the mud gas datasets. In order to proceed with the proposed methodology steps, it was selected for each component an empirical EEC value. These empirical values were provided by the mud logging company, which determined these sets of values with several extraction efficiency tests done in different wells around the world.

Despite all the above comments it was possible to find similar compositional behavior in the Pixler plot between the mud gas sample and the downhole fluid collected at surface. As mentioned in chapter 4 this can be easily understood if taken into consideration that collection conditions for both samples were quite similar.

When comparing raw mud gas data with downhole fluid samples, some compositional differences became evident. Nevertheless, due to the similar fluid behavior in the Pixler plot of both samples, it proves their common origin.

After the application of the extraction efficiency coefficients to the mud gas data, it became much closer to the BHS RG composition, which had been considered as the real reservoir fluid composition. The main compositional differences occurred for the butane and pentane fractions. This conclusion is also supported by the relative error analysis.

The developed predictive model was able to predict the molar concentration of methane, ethane, propane, n-butane and n-pentane. For iso-butane and iso-pentane, molecules present in low concentrations, the proposed model has the lowest predictability power.

It is important to stress that the regressions used for the predictive model accounted only with seven data points. Therefore, the added value of this project is the developed procedure and the qualitative indication of the relationship between the corrected mud gas and the bottomhole recombined gas analysis.

There are several possible ways to upgrade this research. One interesting step that can be tested is a clean oil based mud run through the gas system before the start of the drilling operation. This information can be used to minimize the noise coming in the mud gas log from oil based mud contamination. Without this contamination factor will be easier to pick the real gas peaks to proceed with the analysis.

The model should be updated with a larger dataset. Another essential change that should be implemented is the feeding of data only with real extraction efficiency coefficients. This should help to reduce the regression uncertainty associated to the heavier components (butane and pentane).

It could also be interesting to expand the range of gas components studied. However, in this case is necessary an even more rigorous quality control check. The effect of noise and errors will have a considerable impact in low gas concentration fractions, which will probably mask the real data.

Nevertheless, with the correct application of the developed procedure, stressing the quality control stage, this model can be upgraded to heavy gas analysis and give a very positive input to the real time advanced formation evaluation field.

Taking into account all the assumptions, the results and the conclusions, it is safe to say that advanced gas analysis in real time can be a useful and, also, a powerful tool to adjust well testing strings, sampling points, and focus the formation evaluation program on the spotted anomalies. The importance of advanced gas analysis information becomes even more noticeable when borehole instability problems or other hostile circumstances are found at the well. In this kind of situations where no electric log can be run, mud gas analysis may be the only formation evaluation tool available to provide hydrocarbon type information.

To conclude, it is worth to mention that mud gas samples and bottomhole samples were collected under different conditions, at different times, and analysed through different techniques. Nevertheless it is possible to extract good and valid information from the surface gas data with the right tools and procedures.

References

[1] Beda G., Quagliaroli R., Segalini G., Barraud A., Mitchell A., 1999, Gas While Drilling (GWD): *A Real Time Geologic and Reservoir Interpretation Tool*, SPWLA conference, Oslo.

[2] Haworth J., Sellens M., Gurvis R., 1984, Reservoir Characterization by analysis of light Hydrocarbons Shows, SPE 12914.

[3] Capone G., Budi Riyanto L., Carugo C., Ferroni G., *Advanced Mud Gas Detection System Improves Formation Fluid Characterization while Drilling in Challenging Indonesia Deepwater: A Case History*., 2012, Indonesian Petroleum Association Convention & Exhibition, Jakarta, Indonesia.

[4] Cobenas R.H., Crotti M.A., 1999, *Volatile Oil. Determination of Reservoir Fluid Composition From a Non-Representative Fluid Sample*, SPE 54005.

[5] Ferroni G., Rivolta F., Schifano R., 2012, *Improved Formation Evaluation While Drilling with a New Heavy Gas Detector*, SPWLA D 11 00183.

[6] Haworth J.H., Sellens M., Whittaker A., 1985, *Interpretation of hydrocarbon shows using light (C1-C5) hydrocarbon gases from mud-log data,* AAPG Bulletin 69.

[7] McKinney D., Flannery M., Elshahawi H., Stankiewicz A. and Clarke E., 2007, *Advanced Mud Gas Logging in Combination With Wireline Formation Testing and Geochemical Fingerprinting for an Improved Understanding of Reservoir Architecture*, SPE 109861, SPE Annual Technical Conference and Exhibition, California, USA.

[8] Newton S., Liu C., Al-Dawish M.S., Al-Harbi M., Esterabadi J., Shoeibi A., and Ferroni G., *The Application of Mud Gas Analysis in the Evaluation of a Complex Carbonate Reservoir,* 2014, SPWLA Symposium, Abu Dhabi UAE, paper 1449.

[9] Pinna G. N., Law, D.J., 2008, *Advanced in Mud Gas Interpretation Whilst Drilling*, SPWLA 49th Annual Logging Symposium, Edinburgh, Scotland, United Kingdom.

[10] Barbieri C., Mazzoni S., Abbruzzi G., Ferroni G., 2015, *Advances in Detection and Interpretation of Hydrocarbons, Non-Hydrocarbons and Noble Gases While Drilling*, OMC Conference, Ravenna.

[11] Wenger L.M., Pottorf J., Macleod G., Otten G., Dreyfus S., Justwan H. and Sekula E., 2009, *Drill-Bit Metamorphism: Recognition and Impact on Show Evaluation*, SPE 125218, SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA.

[12] Ferroni G., Prà F., 2010, Advanced Surface Logging technologies provide solutions for deepwater drilling and formation evaluation, DOT 138-2010, Deep Offshore Technology International, Amsterdam, The Netherlands.

[13] Pixer B., 1969, Formation Evaluation by Analysis of Hydrocarbon Ratios, Journal of Petroleum Technology, 665 – 670.

[14] Elshahawi H., Hows M., Dong C., Venkataramanan L., Mullins O., McKinney D., Flannery M. Hashem M., 2007, Integration of Geochemical, Mud Gas and Downhole Fluid Analyses for the Assessment of Compositional Grading - Case Studies, SPE Annual Technical Conference and Exhibition, Anaheim, California.

[15] Mercer, R., 1963, Detection of Gas in Drilling Mud - Value and Limitations, Part 2, World Oil, December.

[16] Mercer R., 1968, The Use of Flame Ionization Detection in Oil Exploration, Second Formation Evaluation Symposium of the Canadian Well Logging Society, Calgary, Alberta, Canada.

[17] Aghar H., Carie M., Elshahawi H., Pinguet B., Takla E., Theuveny B., 2007, The expanding scope of well testing, Schlumberger Oilfield Review, Texas, USA.

[18] Freyss H., Guieze P., Lestelle K., PVT Analysis for oil reservoirs, Technical Review, Volume 37, Number 1.

[19] Norman J. Hyne (2012). Petroleum Geology, Exploration, Drilling & Production (3rd ed.). Tulsa, Oklahoma: Pennwell Corporation.

[20] Adam T., Keith K., Martin E., Young Jr. (1991). Applied Drilling Engineering (2nd ed.). Richardson, Texas: Society of Petroleum Engineers.

[21] Schlumberger Wireline and Testing (1998), Introduction to Well Testing. Bach, England: Phi solutions.

[22] Whittaker A. (1991), The Mud Logging Handbook. Valejo, California: Aegis Group.

[23] Baker Hughes INTEQ(1999), Geological Procedures. Houston, United States of America.

[24] Roussennac B., *Gas Condensate Well Test Analysis*, 2001, MSc thesis, Stanford University, United States of America.

[25] D. Kandel, R. Quagliaroli, G. Segalini, B. Barraud, Improved Integrated Reservoir Interpretation using the Gas While Drilling (GWD) data, 2000, SPE 65176, Paris.

[26] VV. AA., QGM – Quantitative Gas Measurement system User's Guide, 1998, Gas Research Institute of Chicago, IL and Texaco Inc., Houston TX.

[27] Liege X., Dissolution of light hydrocarbons in drilling muds, prediction of the nature of reservoir fluids based on gas shows, 2006, PhD Thesis, Technical University of Denmark, Denmark.

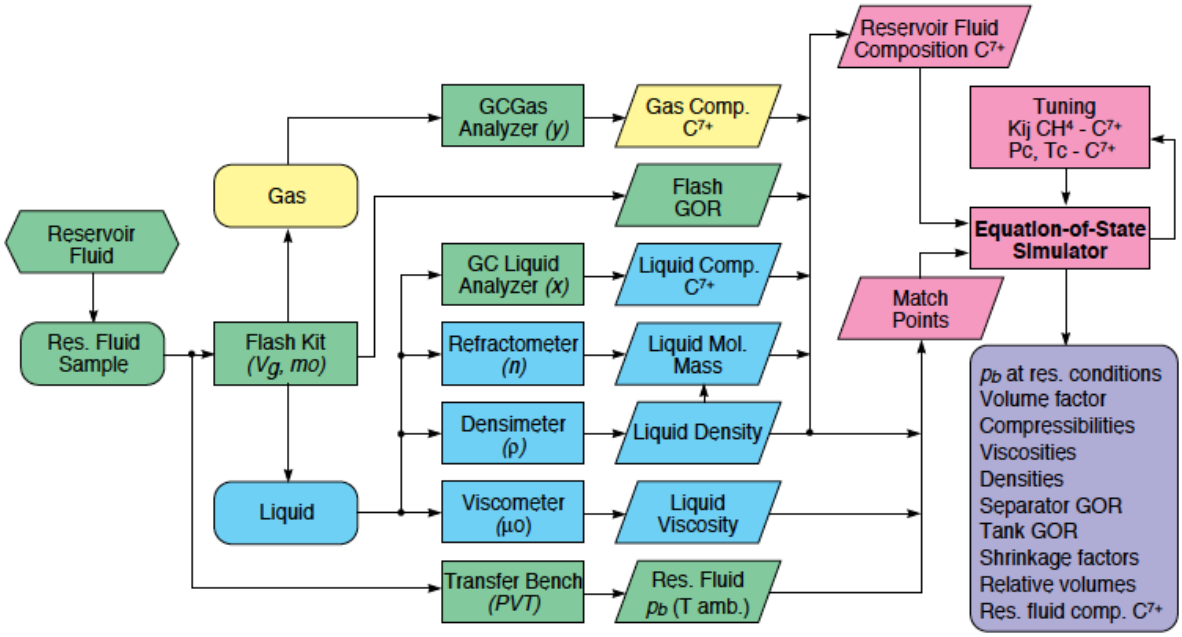
[28] Pinna G. N., Mud gas analysis in formation evaluation, 2012, SPE Talk, Geneva, Switzerland.

[29] Ferroni G., Rivolta F., Schifano R., *Advanced Formation Evaluation While Drilling with a New Heavy Gas Detector*, 2011, AAPG International Conference & Exhibition, Milan, Italy.

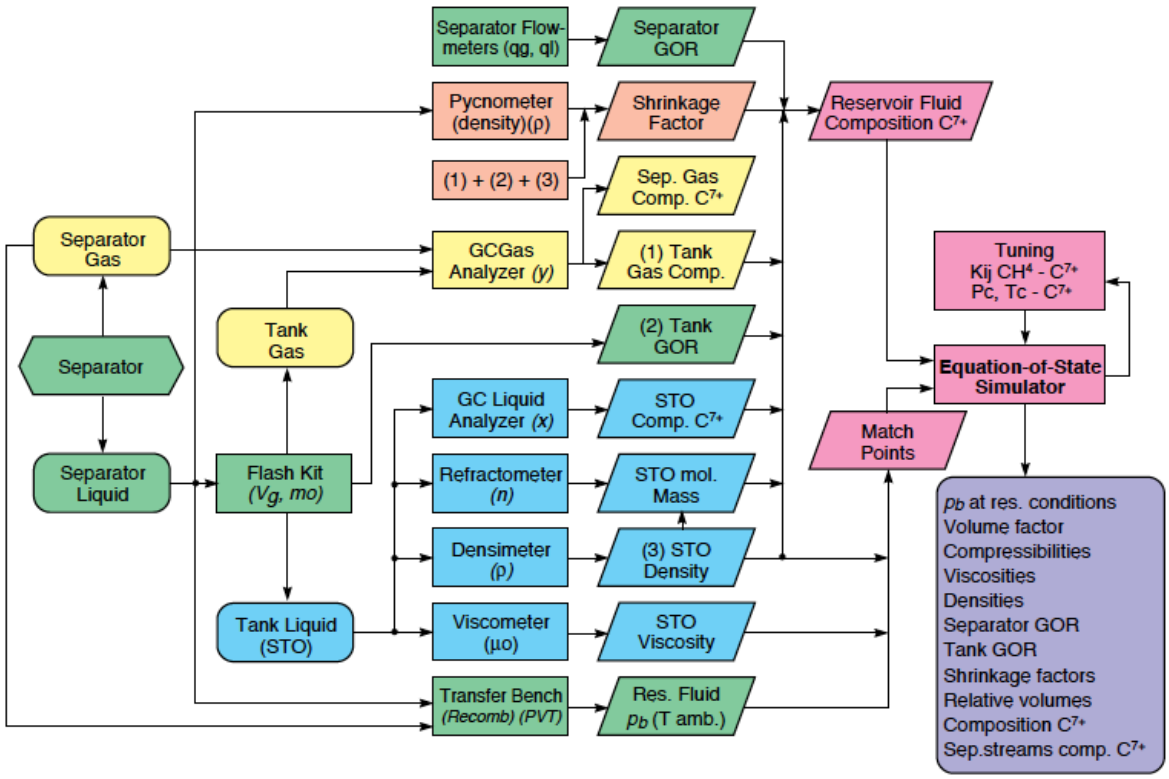
[30] Ferroni G., Uncertainties in Hydrocarbon Detection While Drilling: what does reliable really mean, 2013, SPWLA Abu Dhabi Topical Conference, Abu Dhabi, United Arab Emirates.

[31] Ferroni G., Surface Logging Data in Fractured Reservoirs, 2010, SPE Fractured Reservoirs Development: Challenges and Opportunities, Kuwait City, Kuwait.

Appendix A – Flowchart of downhole fluid tests

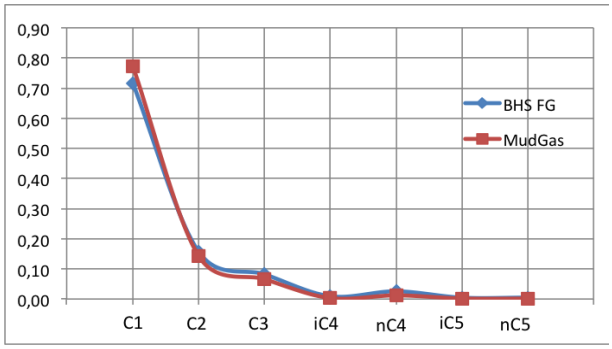


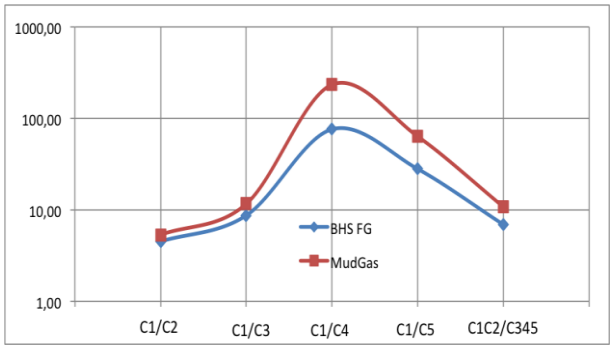
Flowchart of the process for reservoir samples [21].



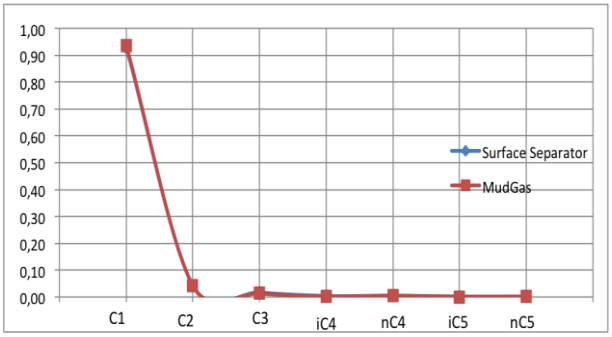
Flowchart of the process for separator samples [21].

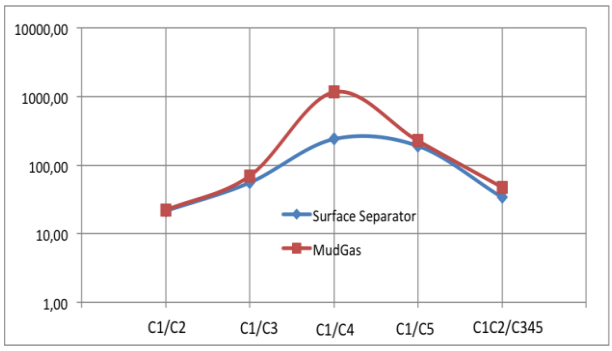
Appendix B – Data comparison for each well



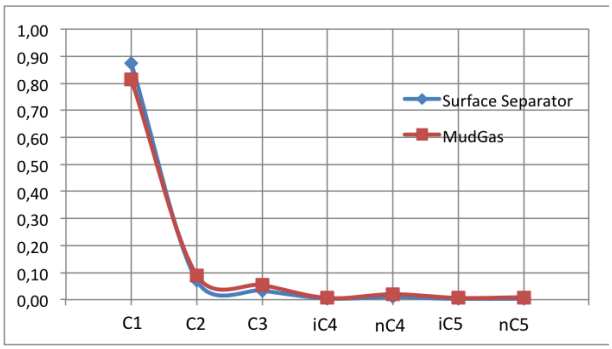


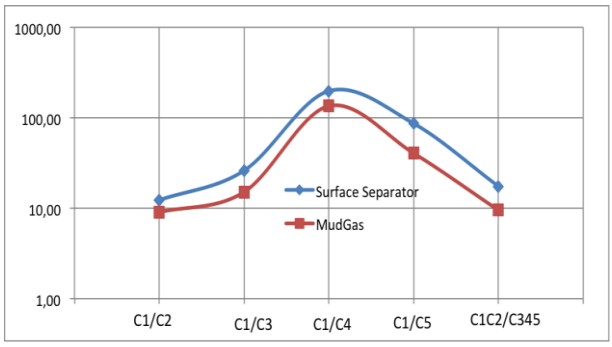
Data comparison for well 3.



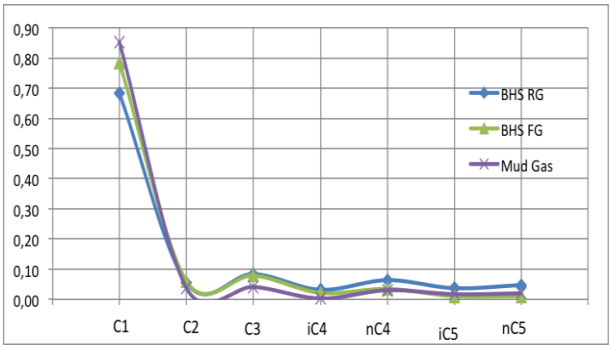


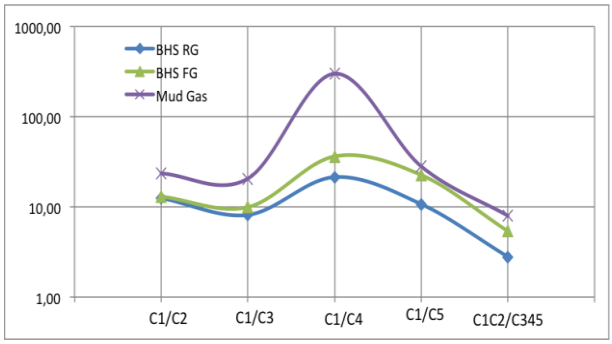
Data comparison for well 4.



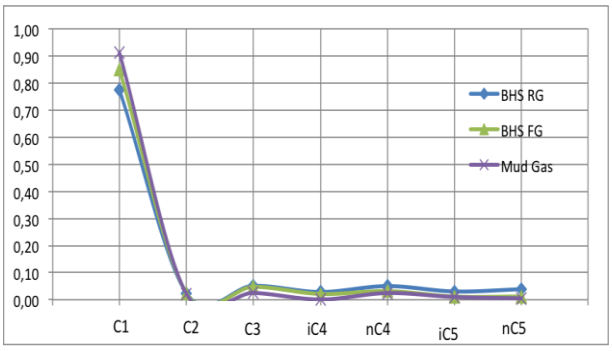


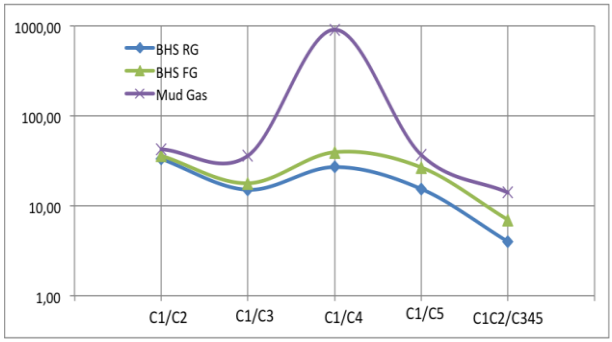
Data comparison for well 5.



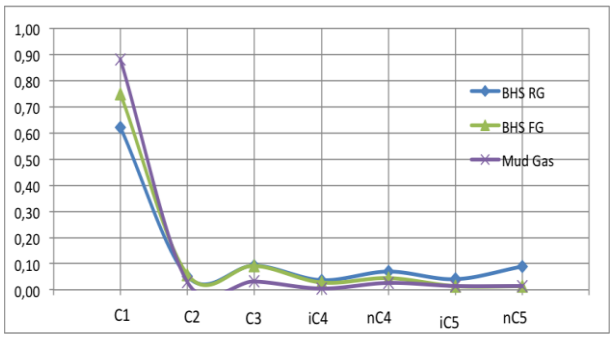


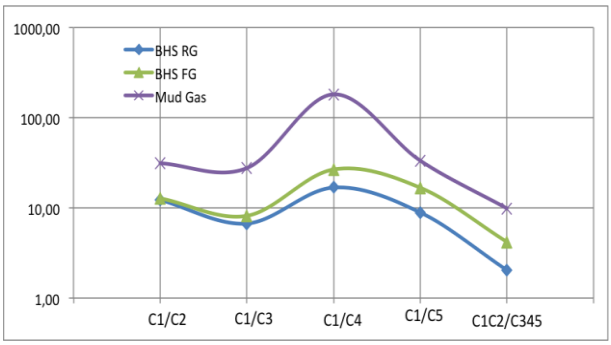
Data comparison for well 8 depth 1.





Data comparison for well 8 depth 2.





Data comparison for well 8 depth 3.

Appendix C - Numerical ratios of fluids comparison

Well 1 – Data for composition plot.

Ratios	Surface Separator	MudGas	BHS FG	BHS RG	Mud Gas EEC
$C_1/\Sigma C_i$	0,77	0,80	0,63	0,60	0,68
$C_2/\Sigma C_i$	0,13	0,09	0,14	0,14	0,10
$C_3/\Sigma Ci$	0,07	0,06	0,12	0,12	0,10
$iC_4/\Sigma C_i$	0,01	0,01	0,03	0,03	0,02
$nC_4/\Sigma C_i$	0,01	0,01	0,05	0,06	0,02
$iC_5/\Sigma C_i$	0,00	0,02	0,02	0,03	0,06
$nC_5/\Sigma C_i$	0,00	0,01	0,02	0,03	0,02

Well 1 – Data for Pixler Plot.

Ratios	BHS FG	MudGas	Surface Separator	BHS RG	Mud Gas EEC
C_1/C_2	4,34	8,86	5,70	4,27	6,48
C_1/C_3	5,38	12,96	10,93	5,08	6,96
C_1/C_4	24,28	78,09	82,15	21,06	18,00
C_1/C_5	12,68	96,02	57,07	10,39	8,20
$\sum C_{1-2}/\sum C_{3-5}$	3,40	8,13	9,16	2,84	3,59

Well 2 – Data for composition plot.

Ratios	Surface Separator	MudGas	BHS FG	BHS RG	Mud Gas EEC
$C_1/\Sigma C_i$	0,86	0,87	0,81	0,77	0,79
$C_2/\Sigma C_i$	0,09	0,08	0,11	0,10	0,11
$C_3/\Sigma Ci$	0,04	0,03	0,05	0,06	0,06
$iC_4/\Sigma C_i$	0,00	0,00	0,01	0,01	0,01
$nC_4/\Sigma C_i$	0,01	0,01	0,01	0,03	0,02
$iC_5/\Sigma C_i$	0,00	0,00	0,00	0,01	0,01
$nC_5/\Sigma C_i$	0,00	0,00	0,00	0,01	0,01

Well 2 – Data for Pixler Plot.

Ratios	BHS FG	MudGas	Surface Separator	BHS RG	Mud Gas EEC
C_1/C_2	7,49	10,32	9,27	7,41	7,16
C_1/C_3	15,53	30,48	23,44	13,34	13,61
C_1/C_4	120,86	347,48	198,98	72,51	32,17
C_1/C_5	63,93	129,66	111,75	29,25	43,76
$\sum C_{1-2}/\sum C_{3-5}$	11,95	23,02	18,44	7,24	8,94

Well 3 – Data for composition plot.

Ratios	MudGas	BHS FG
$C_1/\Sigma C_i$	0,77	0,72
$C_2/\Sigma C_i$	0,14	0,16
$C_3/\Sigma Ci$	0,07	0,08
$iC_4/\Sigma C_i$	0,00	0,01
$nC_4/\Sigma C_i$	0,01	0,03
$iC_5/\Sigma C_i$	0,00	0,00
$nC_5/\Sigma C_i$	0,00	0,00

Well 3 – Data for Pixler Plot.

Ratios	BHS FG	MudGas
C_1/C_2	4,53	5,36
C_1/C_3	8,71	11,66
C_1/C_4	76,22	234,19
C_1/C_5	28,05	63,61
$\sum C_{1-2}/\sum C_{3-5}$	6,91	10,80

Well 4 – Data for composition plot.

Ratios	Surface Separator	MudGas
$C_1/\Sigma C_i$	0,93	0,94
$C_2/\Sigma C_i$	0,04	0,04
$C_3/\Sigma Ci$	0,02	0,01
$iC_4/\Sigma C_i$	0,00	0,00
$nC_4/\Sigma C_i$	0,00	0,00
$iC_5/\Sigma C_i$	0,00	0,00
$nC_5/\Sigma C_i$	0,00	0,00

Well 4 – Data for Pixler Plot.

Ratios	MudGas	Surface Separator
C_1/C_2	22,08	21,34
C_1/C_3	69,52	55,57
C_1/C_4	1155,43	239,31
C_1/C_5	226,77	190,54
$\sum C_{1-2}/\sum C_{3-5}$	47,67	34,01

Well 5 – Data for composition plot.

Ratios	Surface Separator	MudGas
$C_1/\Sigma C_i$	0,87	0,81
$C_2/\Sigma C_i$	0,07	0,09
$C_3/\Sigma Ci$	0,03	0,05
$iC_4/\Sigma C_i$	0,00	0,01
$nC_4/\Sigma C_i$	0,01	0,02
$iC_5/\Sigma C_i$	0,00	0,01
$nC_5/\Sigma C_i$	0,00	0,01

Well 5 – Data for Pixler Plot.

Ratios	MudGas	Surface Separator
C_1/C_2	8,98	12,28
C_1/C_3	15,09	26,03
C_1/C_4	135,00	197,69
C_1/C_5	40,57	86,49
$\sum C_{1-2}/\sum C_{3-5}$	9,51	17,47

Well 6 – Data for composition plot.

Ratios	MudGas	BHS FG	BHS RG	Mud Gas EEC
$C_1/\Sigma C_i$	0,64	0,50	0,34	0,35
$C_2/\Sigma C_i$	0,12	0,13	0,10	0,11
$C_3/\Sigma Ci$	0,13	0,20	0,20	0,26
$iC_4/\Sigma C_i$	0,01	0,03	0,05	0,04
$nC_4/\Sigma C_i$	0,04	0,08	0,14	0,12
$iC_5/\Sigma C_i$	0,02	0,02	0,08	0,05
$nC_5/\Sigma C_i$	0,02	0,03	0,11	0,07

Well 6 – Data for Pixler Plot.

Ratios	BHS FG	MudGas	BHS RG	Mud Gas EEC
C_1/C_2	3,73	5,14	3,45	3,04
C_1/C_3	2,44	4,73	1,70	1,34
C_1/C_4	14,76	43,11	6,99	2,17
C_1/C_5	6,12	14,27	2,45	2,84
$\sum C_{1-2}/\sum C_{3-5}$	1,71	3,22	0,76	0,85

Well 7 – Data for composition plot.

Ratios	MudGas	BHS FG	BHS RG	Mud Gas EEC
$C_1/\Sigma C_i$	0,41	0,31	0,20	0,26
$C_2/\Sigma C_i$	0,17	0,20	0,14	0,15
$C_3/\Sigma Ci$	0,21	0,26	0,22	0,25
$iC_4/\Sigma C_i$	0,02	0,04	0,04	0,03
$nC_4/\Sigma C_i$	0,09	0,12	0,17	0,14
$iC_5/\Sigma C_i$	0,03	0,03	0,08	0,07
$nC_5/\Sigma C_i$	0,05	0,04	0,14	0,10

Well 7 – Data for Pixler Plot.

Ratios	BHS FG	MudGas	BHS RG	Mud Gas EEC
C_1/C_2	1,53	2,38	1,42	1,74
C_1/C_3	1,19	1,94	0,92	1,05
C_1/C_4	8,30	17,75	4,83	1,48
C_1/C_5	2,58	4,41	1,19	1,51
$\sum C_{1-2}/\sum C_{3-5}$	1,04	1,43	0,52	0,69

Well 8 Depth 1 – Data for composition plot.

Ratios	MudGas	BHS FG	BHS RG	Mud Gas EEC
$C_1/\Sigma C_i$	0,85	0,78	0,68	0,66
$C_2/\Sigma C_i$	0,04	0,06	0,05	0,04
$C_3/\Sigma Ci$	0,04	0,08	0,08	0,07
$iC_4/\Sigma C_i$	0,00	0,02	0,03	0,01
$nC_4/\Sigma C_i$	0,03	0,03	0,06	0,08
$iC_5/\Sigma C_i$	0,02	0,01	0,04	0,07
$nC_5/\Sigma C_i$	0,02	0,01	0,05	0,08

Well 8 Depth 1 – Data for Pixler Plot.

Ratios	BHS FG	MudGas	BHS RG	Mud Gas EEC
C_1/C_2	13,09	23,33	12,63	18,38
C_1/C_3	9,94	20,60	8,14	9,03
C_1/C_4	36,33	300,44	21,41	7,90
C_1/C_5	22,58	28,17	10,73	4,39
$\sum C_{1-2}/\sum C_{3-5}$	5,38	7,97	2,79	2,27

Well 8 Depth 2 – Data for composition plot.

Ratios	MudGas	BHS FG	BHS RG	Mud Gas EEC
$C_1/\Sigma C_i$	0,91	0,85	0,78	0,81
$C_2/\Sigma C_i$	0,02	0,02	0,02	0,03
$C_3/\Sigma Ci$	0,03	0,05	0,05	0,05
$iC_4/\Sigma C_i$	0,00	0,02	0,03	0,00
$nC_4/\Sigma C_i$	0,02	0,03	0,05	0,06
$iC_5/\Sigma C_i$	0,01	0,01	0,03	0,04
$nC_5/\Sigma C_i$	0,01	0,01	0,04	0,02

Well 8 Depth 2 – Data for Pixler Plot.

Ratios	BHS FG	MudGas	BHS RG	Mud Gas EEC
C_1/C_2	36,26	42,94	32,96	31,57
C_1/C_3	17,81	35,99	15,08	17,47
C_1/C_4	39,47	909,74	26,98	13,55
C_1/C_5	26,76	36,88	15,40	13,90
$\sum C_{1-2}/\sum C_{3-5}$	6,99	14,03	3,99	5,08

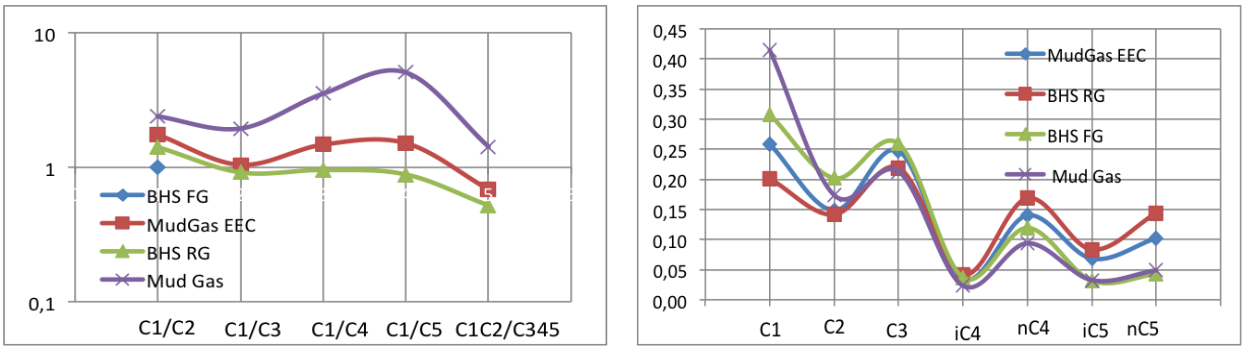
Well 8 Depth 3 – Data for composition plot.

Ratios	MudGas	BHS FG	BHS RG	Mud Gas EEC
$C_1/\Sigma C_i$	0,88	0,75	0,62	0,74
$C_2/\Sigma C_i$	0,03	0,06	0,05	0,03
$C_3/\Sigma Ci$	0,03	0,09	0,09	0,06
$iC_4/\Sigma C_i$	0,00	0,03	0,04	0,01
$nC_4/\Sigma C_i$	0,03	0,04	0,07	0,06
$iC_5/\Sigma C_i$	0,01	0,01	0,04	0,05
$nC_5/\Sigma C_i$	0,01	0,01	0,09	0,05

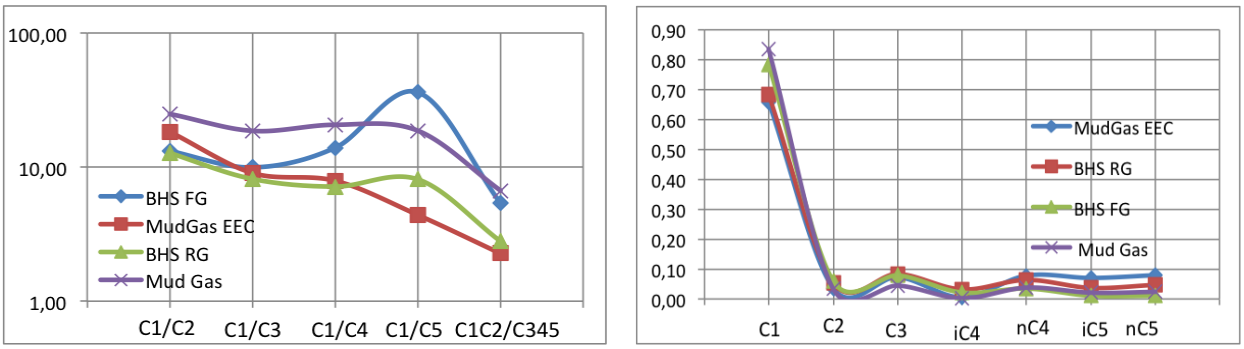
Well 8 Depth 3 – Data for Pixler Plot.

Ratios	BHS FG	MudGas	BHS RG	Mud Gas EEC
C_1/C_2	12,88	31,14	12,25	22,90
C_1/C_3	8,16	27,62	6,70	13,41
C_1/C_4	26,70	181,85	16,82	10,82
C_1/C_5	16,75	33,50	8,90	7,13
$\sum C_{1-2}/\sum C_{3-5}$	4,20	9,87	2,04	3,40

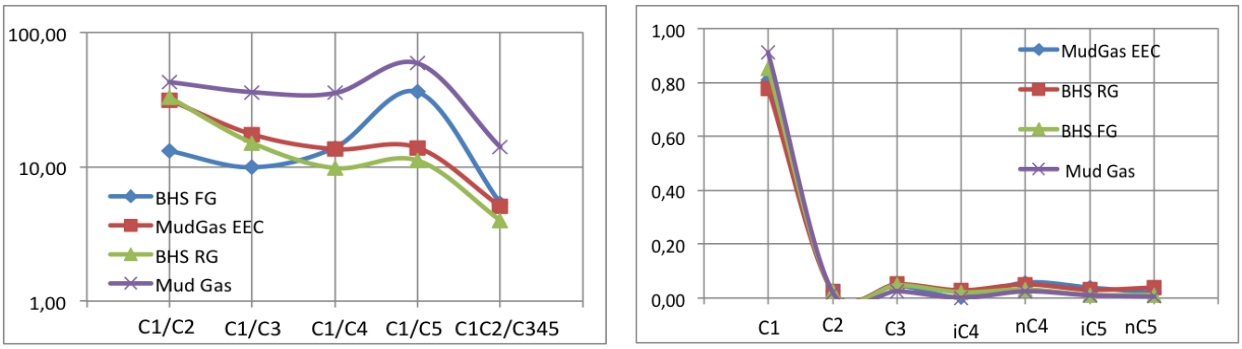
Appendix D – Mud gas EEC comparison for each well



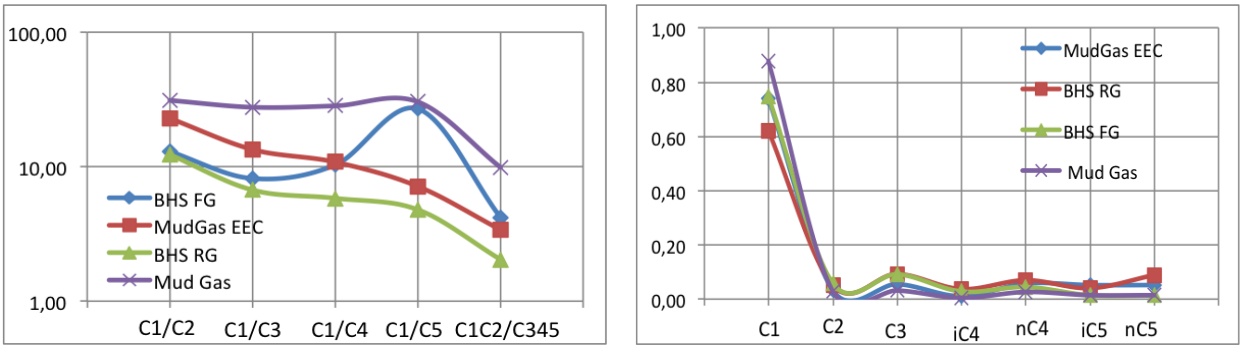
Well 7 - Comparison between all the sample in the Pixler plot (left) and concentration plot (right).



Well 8 Depth 1 - Comparison between all the sample in the Pixler plot (left) and concentration plot (right).



Well 8 Depth 2 - Comparison between all the sample in the Pixler plot (left) and concentration plot (right).



Well 8 Depth 3- Comparison between all the sample in the Pixler plot (left) and concentration plot (right).

Appendix E - Relative errors

Relative errors for each component between mud gas with EEC and bottomhole flashed gas samples.

C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5
0,08	0,28	0,17	0,20	0,66	2,17	0,36
0,03	0,01	0,11	0,00	0,40	2,17	2,57
0,30	0,15	0,27	0,18	0,48	1,23	1,56
0,16	0,27	0,05	0,06	0,18	1,16	1,40
0,05	0,09	0,03	0,89	0,81	2,29	0,61
0,01	0,44	0,40	0,62	0,29	2,68	2,77
0,16	0,40	0,08	0,75	1,25	5,55	6,24

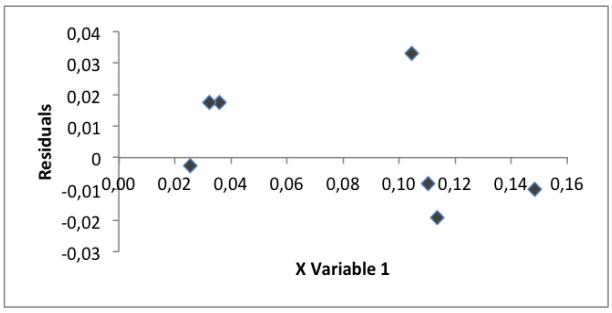
Relative errors for each component between mud gas with EEC and bottomhole recombined gas samples.

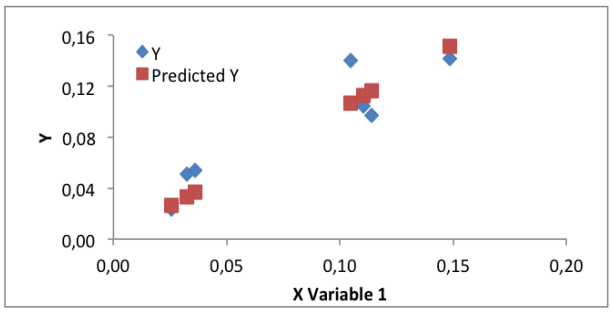
C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5
0,13	0,25	0,17	0,27	0,71	1,10	0,18
0,02	0,06	0,00	0,37	0,33	0,26	0,36
0,03	0,17	0,31	0,17	0,12	0,31	0,36
0,28	0,05	0,13	0,16	0,17	0,18	0,29
0,04	0,09	0,10	0,92	0,14	0,27	0,50
0,19	0,36	0,40	0,71	0,17	0,28	0,42
0,04	0,34	0,13	0,83	0,23	0,90	0,68

Relative errors for each component between bottomhole flashed gas samples and recombined gas samples.

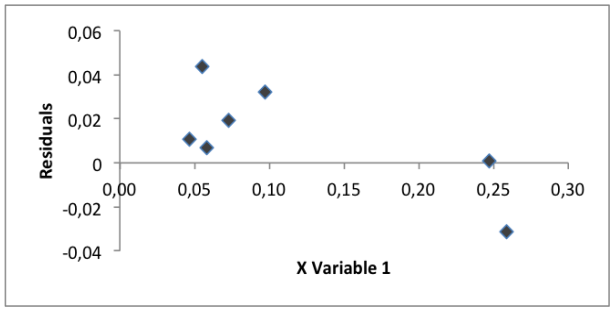
C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5
0,05	0,03	0,01	0,09	0,14	0,34	0,40
0,05	0,04	0,10	0,37	0,52	0,77	0,82
0,48	0,37	0,03	0,30	0,41	0,69	0,75
0,53	0,43	0,18	0,11	0,29	0,62	0,70
0,15	0,11	0,06	0,32	0,45	0,71	0,77
0,10	0,00	0,07	0,25	0,37	0,61	0,69
0,21	0,15	0,01	0,24	0,36	0,65	0,85

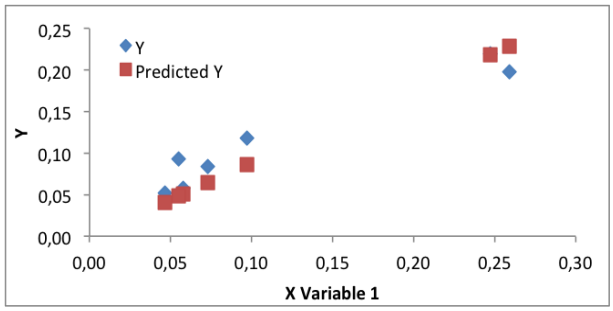
Appendix F – Residual and line fit plots



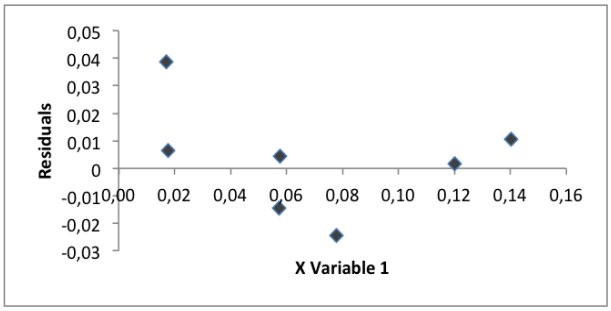


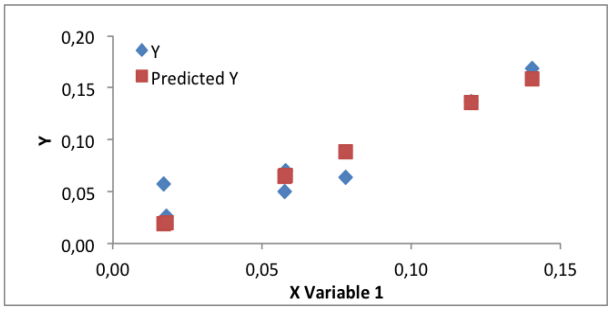
Residual plot (left) and Line fit plot (right) for ethane regression.



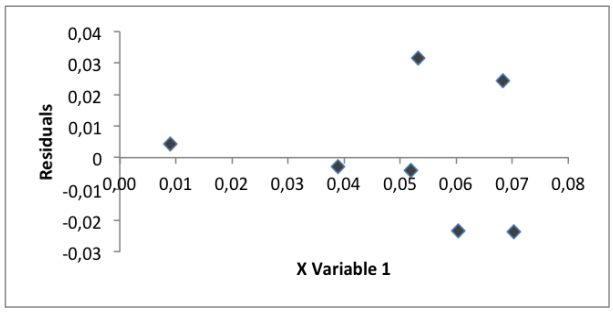


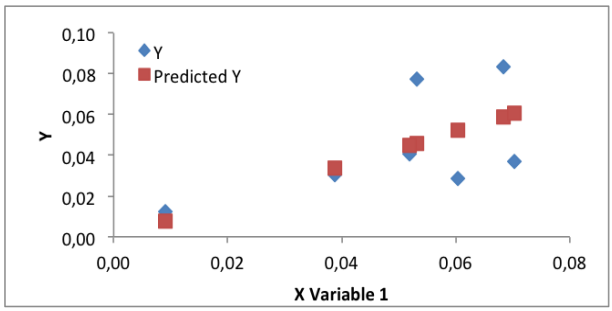
Residual plot (left) and Line fit plot (right) for propane regression.



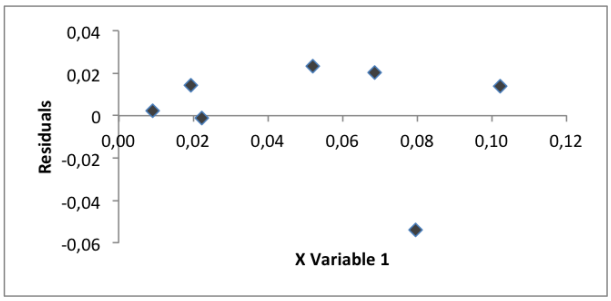


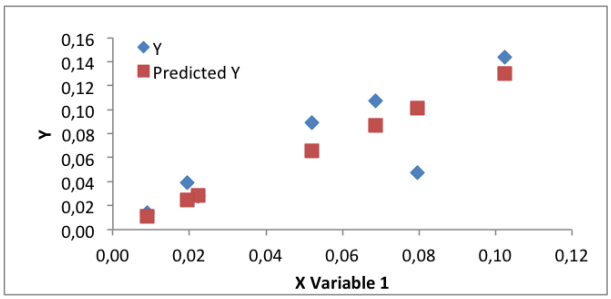
Residual plot (left) and Line fit plot (right) for normal-butane regression.





Residual plot (left) and Line fit plot (right) for iso-pentane regression.





Residual plot (left) and Line fit plot (right) for normal-pentane regression.