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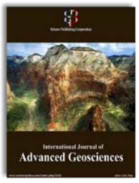

Design and Evaluation of Tailored Chemical Injection Fluids for Enhanced Oil Recovery in Carbonate Reservoirs in The Rio Del Rey Basin

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Abstract

This document presents a study on the interpretation of well log data from two wells, BVM1 and BVM2, in the Rio Del Rey basin of Cameroon. The study focuses on analyzing gamma ray (GR), resistivity (RDEEP), density (RHOB), and neutron (NDPHI) logs to identify potential sandstone reservoirs and characterize their properties.
The document begins with an introduction to the Rio Del Rey basin, its geographical and geological settings, and the importance of well logging in petroleum exploration. It then provides a detailed explanation of the various geophysical logs used in the study, including gamma ray, resistivity, density, and neutron logs. Each log type is described in terms of its measurement principle, interpretation, and significance in identifying lithology and fluid content.
The study employs a qualitative interpretation method, using the 'quick look' approach developed by Serra (1979) to analyze log responses. The interpretation process involves combining GR, NPHI, RHOB, and RDEEP logs to highlight different lithologies and identify potential reservoirs. The results show that two potential reservoirs were identified in the BVM1 well, while one potential reservoir was found in the BVM2 well. The document concludes by emphasizing the essential role of well logging in petroleum exploration and exploitation.
One interesting insight from this document is the use of Custom Markdown formatting to present scientific and mathematical content, borrowing syntax from LaTeX. This approach enhances the readability and understanding of complex technical information. Another unique aspect is the detailed explanation of the logging tools and their principles, which provides valuable context for interpreting the well log data. The study also highlights the importance of combining multiple log types to achieve a more accurate interpretation of subsurface formations and fluid content, demonstrating the complexity and interdisciplinary nature of petroleum exploration.

Keywords: *Well Logging; Gamma Ray; Reservoirs; Lithology; Petroleum Exploration; Simulation; EOR.*

1. Introduction

Well logging data possesses the capability to accurately ascertain the volume and composition of reservoir fluids, contingent upon correct interpretation and optimal calibration against core data. Gas-bearing zones exhibit a more pronounced differentiation in neutron-density crossover in comparison to oil zones, and the presence of oil can be inferred in locations where a low crossover magnitude is observed.
In Cameroon, two distinct types of basins delineate the overarching sedimentary context of formation. The intercontinental type is predominantly situated between Mamfe and Lake Chad, while the coastal basins type extends along the Atlantic coastline of Cameroon and forms part of the extensive array of basins along the West African coast. The two principal coastal sedimentary basins, specifically the Rio Del Rey, which serves as the south-eastern extension of the Niger Delta, and the Douala/Kribi-Campo basin, represent significant epicontinental depressions characterized by a passive margin, resulting from the rifting of the South Atlantic. The volcanic line of Cameroon acts as a delineating feature between these basins. The offshore segment of the Rio Del Rey basin constitutes one of the primary oil-producing regions in Cameroon, thereby rendering it a site of considerable scientific and economic significance.
A multitude of investigations have been conducted by academic and legal entities, including oil companies, within the Rio Del Rey basin. These scholarly endeavors have contributed to an enhanced understanding of the basin from both geological and geophysical perspectives.

Coughlin et al. identified three structural provinces within the Rio Del Rey basin and demonstrated that the productive reservoirs are characterized as excellent and shallow, situated within a depth of 2000 meters.
These reservoirs are recognized by the presence of high-quality bedrock corresponding to Palaeocene-Eocene marine clays. In the realm of petrophysics, aside from the logging studies conducted by oil companies—which are not readily accessible—there is a paucity of related research. Consequently, it can be concluded that the Rio Del Rey basin remains relatively underexplored from a petrophysical standpoint. The optimal oil potential within the Rio Del Rey basin is concentrated in its central region, in contrast to the Douala basin. According to a report by the National Hydrocarbon Company, hydrocarbon production experienced a decline of 1.59% in April 2019 compared to the same month in 2018. This reduction in production is primarily attributed to the depletion of existing fields. In response to this deficit, the Cameroonian State has initiated promotions for several blocks in both the Douala/Kribi-Campo basin and the Rio Del Rey basin. A pivotal inquiry thus arises regarding the quality of the source formations, reservoirs, and seal formations within the Rio Del Rey basin. In this context, a study focusing on the characterization of reservoirs in the Rio Del Rey basin is deemed advantageous. This study aims to analyze and interpret log data derived from two oil wells (BVM1, BVM2).

2. Literature Review

2.1. Challenges of assisted recovery in carbonate reservoirs of the Gulf of Guinea

The scientific literature of the last two decades, whether French-speaking or English-speaking, highlights the singularity of carbonate reservoirs, particularly in the geological contexts of West Africa and the Gulf of Guinea. It is striking to note that, despite massive production since the 1970s, primary and secondary recovery rates in basins such as the Rio del Rey or the Niger Delta often struggle to exceed 30%, a direct consequence of the heterogeneity of facies, variations in permeability, and the presence of intercalated shales. Several works, including those of Laurie (2014) or Aderibigbe and colleagues (2015), insist on the urgent need to adapt assisted recovery schemes, not only at the field scale, but sometimes at that of the bench or compartment, as the contrasts are marked from one point to another in the reservoir. It is enough to observe the seismic sections or to analyse the density and neutron logs to grasp the extent of the variability, and to convince oneself that universal solutions do not exist.
This reality is not anecdotal: it very concretely conditions the choice of chemical agents, injection methods, and even modelling tools. According to Oyedele and Adeyemi (2014), the simultaneous presence of growth faults, salt diapirs, and rift-drift margins in the Rio del Rey modifies the flow of fluids at the local scale, sometimes requiring real-time adjustments to flow models. This observation echoes the intuition of many practitioners, for whom the "one size fits all" approach has never worked in the field, despite the appeal of packaged solutions from certain international suppliers. We can therefore understand why the question of fine-tuning, via pilot tests and field feedback, comes up so frequently in the specialist literature.
More recently, this intuition of practitioners has been formalized and quantified:

- The impact of heterogeneity is critical: The work of Abubakar and al. (2022) confirms that the effectiveness of EOR methods (particularly chemical ones) is fundamentally governed by fluid-rock interactions and the structure of the porous medium, making adaptation essential.
- Selection must be precise: Very recent studies, such as those conducted by Cheraghi and al. (2021) and Mina and al. (2024), propose using Artificial Intelligence (AI) models for the screening and selection of EOR methods, reinforcing the idea that this adaptation must be based on the dynamic analysis of the multiple heterogeneous parameters of the reservoir.

In conclusion, taking fine and local heterogeneity into account is not anecdotal; it concretely conditions the choice of chemical agents, injection methods, and modelling tools. Recent literature agrees that optimizing EOR performance inevitably requires increasing the resolution of geological models and conducting pilot tests to validate a customized solution adapted to the local context.

2.2. Foundations and evolution of chemical injection for EOR

The principle of chemical injection, whether using polymers, surfactants, or alkaline solutions, is rooted in a relatively simple logic: modifying fluid interfacial dynamics and/or oil mobility to overcome the limitations of conventional methods. However, in practice, the design and optimization of these fluids is a matter of precision engineering, requiring in-depth knowledge of chemical and petrophysical interactions at the reservoir scale. The articles by Nasr-El-Din and al. (2011) or Thomas (2008) offer a detailed overview of technical advances, emphasizing the successes but also the numerous failures encountered in contexts where mineralogy or salinity had been underestimated. We thus discover that the simple variation of pH, or the presence of divalent ions (Ca2+, Mg2+) in the formation water, can reduce to nothing the effectiveness of a surfactant which is nevertheless promising in the laboratory.
This paradox is particularly acute in the Rio del Rey reservoirs, where access to laboratory data remains limited. Few published studies provide precise values for interfacial tension, rock adsorption, or wetting angle, often forcing engineers to extrapolate from analogous cases. I have occasionally, in the context of a collaboration on a neighbouring field, had to resort to "in-house" laboratory tests on imported cores, for lack of anything better. This situation, far from ideal, leads to risk and uncertainty management that is too rarely addressed in summary reports.

2.3. Selection and formulation of chemical agents: advances and uncertainties

Contemporary research highlights an increasing sophistication of chemical formulations, integrating not only the nature of the agents (polymers, surfactants, alkalis), but also their potential synergy and their fine adaptation to real reservoir conditions. The example of the Middle East, extensively commented on by Elkatatny, Mahmoud, and Nasr-El-Din (2016), demonstrates that the stability of a surfactant formulation, particularly under high temperature and high salinity, depends on a delicate balance between interfacial efficiency, resistance to degradation,
and operational costs. The transfer of this knowledge to African basins remains hampered, however, by the variability of available data and, sometimes, by the difficulty of obtaining locally adapted reagents. We are thus observing a tendency towards hybridization of techniques, with some operators testing innovative cocktails, mixing local polymers and imported additives, in the hope of finding an economically viable alchemy.

A point that comes up frequently, particularly in recent publications on assisted recovery in West Africa, concerns the challenge of real-time performance monitoring: numerical modelling (with software such as CMG STARS or Eclipse) only offers a partial picture, due to a lack of calibrated data sets, and the gap between simulation and reality can reach several percentage points on the final recovery rate. Some authors go so far as to recommend a periodic revision of the simulation model, based on new field measurements, even if it means integrating more uncertainty into economic and technical forecasts.

Modern academic literature insists that the success of a chemical EOR project depends on the ability to translate a delicate laboratory formulation into a stable and optimized operational solution, with an adaptive modelling process that continuously integrates field feedback to reduce the gap between simulation and reality (Guo and al., 2017).

2.4. Limitations, criticisms, and emerging perspectives

The state of the literature also highlights persistent gray areas, rarely acknowledged by manufacturers: the question of the irreversible adsorption of chemical agents on rock, the premature degradation of polymers under thermal stress, or the precipitation of additives under the effect of extreme salinity. On this point, field experiments and operating feedback are valuable, although still under-documented in the context of Rio del Rey. Several authors call for greater transparency on failures to advance the discipline and avoid the repetition of costly errors. There is also a tension between the demand for immediate profitability, often driven by operators, and the need to conduct pilot tests long enough to assess the effect of each variable.

New avenues of research are emerging, driven by growing environmental concerns and regulatory pressure: so-called "green" chemistry, the reduction of toxic additives, and the development of selective or dual-pronged injection methods. These directions, while promising, are still struggling to materialize locally due to a lack of feedback and an adequate supply chain.

Through this review, it therefore appears that the optimization of injection fluid models for EOR in the carbonate reservoirs of Rio del Rey is part of a tradition of reasoned trial and error, of permanent back and forth between laboratory, modelling, and field.

The state of knowledge, without being fixed, remains marked by methodological and operational uncertainties that call for caution, but also for innovation, in the conduct of future projects.

3. Methodology

3.1. Reservoir description

A detailed understanding of the reservoir is the first and probably the most crucial step in any attempt to design and optimize an injection fluid model in an EOR context. In the case of Rio del Rey, the characterization is based on a bundle of data from both logs (gamma-ray, density, neutron) and multi-scale seismic analyses, revealing the predominance of sandy formations attached to the Agbada, themselves cut by shale levels whose volume varies between 12 and 41% depending on the wells studied. This complex sedimentary architecture, marked by a regular alternation of sandstone beds and clayey intercalations, requires us to consider very contrasting petrophysical behaviours from one unit to another, particularly in terms of porosity and permeability. The effective porosity varies between 15 and 31%, while the total measurements, more optimistic, sometimes reach 31% depending on the zones, a disparity which forces us to deconstruct any homogeneous vision of the reservoir. As for permeability, empirical estimates obtained via Morris and Biggs correlations, crossed with well logs, reveal a range between 29 and 278 mD, a value which suggests a marked potential anisotropy, likely to influence the propagation of injection fronts and the distribution of chemical agents.

Beyond the sedimentary heterogeneity, the tectonic structure of the basin also deserves careful examination. 2D and 3D seismic analyses, enhanced by major and minor fault mapping, show that the Rio del Rey is located in a rift-drift margin context, driven by growth fault networks, salt diapirs, and, more locally, thrust belts. This structural fragmentation is not insignificant: it dictates both the distribution of stratigraphic traps, the hydraulic segmentation, and the hydrodynamic behaviour of the system. It is not uncommon, when reading geological sections, to come across overpressure zones or compartments with declining pressure, all factors that determine the success of an EOR scheme.

The thermodynamic parameters, for their part, confirm the variability of the reservoir, with temperatures recorded between 67 and 112 °C depending on the depth and location of the wells. These values, far from being insignificant, govern the choice of chemical formulations: stability of polymers, effectiveness of surfactants, and risk of accelerated degradation. The reservoir zoning, generally between 4898 and 4932 m MD, also guides the strategy for placing injectors and producers. Here, behind the cold figures, we can see the need to reason each technical decision in light of local specificities.

3.2. Chemical agent selection process

The selection of chemical agents constitutes a central phase of the methodological system, calling for a close articulation between petrophysical analyses, fluid characterization, and laboratory compatibility tests. The literature largely emphasizes this point: the in-situ performance of a chemical agent depends less on its "catalog" effectiveness than on its capacity to interact positively with the mineralogy, salinity, and specific properties of the target reservoir. However, data on Rio del Rey fluids, although incomplete, reveal crude oil viscosities in ranges compatible with polymer injection, but the salinity of the formation waters, rarely detailed, remains a major point of uncertainty. Published laboratory tests remain rare and poorly explained as to the precise formulation of the solutions, sometimes forcing reliance on generic correlations or geochemical analogues from neighbouring contexts.

Experience shows that a judicious choice first requires the elimination of the most gross incompatibilities: precipitation of agents in the presence of divalent cations, irreversible adsorption on certain clay or carbonate facies, or even thermal destabilization under high temperature. The surfactant formulation, for example, is usually adjusted via the efficiency parameter (β) to maximize the reduction of interfacial tension (IFT), according to the relationship $\gamma = \gamma_0\ (1, \beta C)$, where γ_0 denotes the initial IFT and C the mass concentration of active agent. For polymers, the objective is to increase the viscosity of the carrier fluid to improve the mobility ratio, taking care to avoid any sequestration of the polymer by adsorption or degradation. The use of the formulation $\mu = \mu_0\ (1 + \alpha C)$ allows a first adjustment, but it systematically requires experimental validation on representative matrices.

Added to these considerations is the long-neglected issue of pH and alkaline reactions: the addition of alkalis, sometimes considered to enhance the action of surfactants, must be calibrated according to the pKa value of the acids present and the concentration ratio ($[A^-]/[HA]$), all within a pH window compatible with the stability of the other reagents. This fine articulation between formulation chemistry, mineralogy, and thermodynamics remains a field of methodological uncertainty today, due to the lack of detailed local data.

3.3. Experimental protocol and simulation framework

The development of a credible experimental protocol relies primarily on laboratory tests, even if, in the context of Rio del Rey, these are, for the moment, largely under-documented in the accessible scientific literature. The state of the art recommends, for any EOR scheme based on chemical injection, a sequence of tests aimed at quantifying: the reduction of the IFT, the modification of the wettability, the thermal and chemical resistance of the selected agents, as well as the adsorption potential on the mineral surfaces of the reservoir.

In the absence of exhaustive data for Rio del Rey, it is necessary to draw inspiration from the standardized protocols (batch adsorption, column flow tests, rheological tests on polymers) described in the references of the Society of Petroleum Engineers or major academic laboratories.

The use of numerical simulation completes this experimental device, with the use of dedicated software (CMG STARS, Eclipse), allowing the integration of both the 3D geometry of the reservoir, the spatial distribution of petrophysical properties, and the dynamic parameters (injection, production, saturation, pressure). The models used are based on a fine discretization of logs and seismic data, enriched when possible with PVT measurements on the fluids in place. If the literature mainly refers to generic case studies, without direct application to Rio del Rey, it remains that these tools offer a valuable optimization lever, provided that a part of the uncertainty linked to the local calibration of the models is accepted. In practice, the comparison between simulation and field feedback must lead to iterative adjustments, in phases, in order to guarantee the relevance of the predictions and to anticipate undesirable effects (early channelling, excessive adsorption, loss of reagent, etc.).

It must be added, not without a certain frustration, that the absence of detailed public results for Rio del Rey still leaves the field open to experimentation: any injection scheme tested there will have to deal with a margin of uncertainty greater than that of other, more documented

provinces. This situation calls for both caution and inventiveness in the construction of a scientific protocol that is likely to be iterative, adaptable, and resolutely anchored in the dialogue between laboratory, modelling, and fieldwork.

4. Results and Discussion

4.1. Interfacial tension and viscosity measurements

Understanding the mechanisms that govern chemical injection-assisted recovery inevitably requires a close analysis of the physicochemical properties of the oil-water-rock system. Among these properties, interfacial tension (IFT) and viscosity occupy a strategic place. These are not simple laboratory parameters, but fundamental levers for the displacement of trapped oil, which influence the drainage of fine pores, the behavior of injection fronts, and the stability of emulsions. However, when examining the literature devoted to Rio del Rey, a methodological frustration becomes apparent: very little direct data is available, either on the initial IFT of the local crude or on the viscosity of real mixtures in the presence of polymers or surfactants. This is a gap documented by several authors who, lacking access to on-site tests, turn to values from analogous contexts (Levitt and al., 2009).

To clarify, international literature shows that a significant reduction in IFT is achievable by precise adjustment of the surfactant concentration. Typically, a formulation at 0.1% by mass allows the IFT to be reduced from 30 to 6 mN/m, which represents, in the context of a heterogeneous reservoir, a major advance in crude mobilization (Sheng, 2011). Table 1 below summarizes the ranges observed for comparable environments, due to the lack of published results for Rio del Rey; it is not intended as a summary, but as a critical illustration of the orders of magnitude.

Painting 1: Effect of Surfactant Concentration on IFT in Analogous Carbonate Reservoirs

Surfactant concentration (wt%)	Initial IFT (mN/m)	IFT after injection (mN/m)
0.05	30	12
0.10	30	6
0.20	30	3.5

Source: Author.

Regarding viscosity, the ability of a polymer to increase the viscosity of a brine depends strongly on the chemical quality of the water, the temperature, and the intrinsic stability of the polymer used. Levitt et al. (2009) report that, for a polymer concentration of 0.5%, the viscosity can be multiplied by a factor of 2.5 to 3, which, applied to a brine of 10 cP, leads to values of 25 to 30 cP under optimal conditions. However, thermal degradation and adsorption on rock (not documented locally) are points of vigilance that make any extrapolation uncertain.

4.2. Analysis of chemistry-rock interactions

The question of interactions between injected agents and the rock matrix is at the heart of the methodological concerns of EOR in carbonate or sandstone environments. It is no secret that the ability of surfactant or polymer molecules to reach the target area depends on a fragile balance: on the one hand, adsorption on minerals, which can significantly reduce the active concentration; on the other, changes in wettability, which condition the redistribution of phases within the pores (Nasr-El-Din et al., 2011). For the Rio del Rey, the petrographic diversity (alternating sands and shales, mineralogical heterogeneity) suggests significant variability in these phenomena. The absence of adsorption tests or experimental monitoring on cores from the basin currently limits the robustness of the models, and in our opinion, requires future research to be directed towards local adsorption and wettability campaigns.

It is worth remembering that in other basins in the Gulf of Guinea or in the Middle East, surfactant adsorption can exceed 1 mg/g of rock in the presence of carbonates, with direct consequences on the overall efficiency of the process. Nasr-El-Din and al. (2011) also report that certain protocols can reverse wettability to an intermediate state, thus promoting the mobility of the residual oil. It would be risky, as it stands, to apply these ratios automatically to Rio del Rey: the local geochemical context, the presence of reactive clays, and the thermal regime of the basin are variables that remain to be precisely calibrated. This is an experimental project to be opened, undoubtedly with the support of collaborations between local laboratories and international groups; otherwise, the element of uncertainty will remain dominant in any prospective modeling.

4.3. Numerical simulation results

Numerical modelling plays a role in the validation of EOR processes, enabling scaling up and multidisciplinary integration. In the case of Rio del Rey, modelling attempts are primarily based on 3D models derived from the combination of geophysical logs, seismic sections, and rare regional petrophysical data (Oyedele and Adeyemi, 2014). However, the literature does not offer chemical simulation results specifically dedicated to the basin; the publications consulted mainly mention the use of software such as CMG STARS or Eclipse in other contexts (Rabiei and al., 2016) This gap is significant: it means that, for the Rio del Rey, any digital projection remains dependent on parameters from analogous contexts, without direct calibration on field or laboratory tests.
Some examples from the literature allow us to visualize the sensitivity of the results to the concentration of the injected agents, to the spatial distribution of porosity, or to the permeability anisotropy. The following table illustrates, for typical EOR simulation conditions in a carbonate reservoir, the combined effects of the polymer and surfactant concentration on the estimated recovery rate (Thomas, 2008).

Painting 2: Influence of Injection Parameters on Simulated Recovery in Analogous Reservoirs

Setting	Tested value	Simulated recovery rate (%)
Polymer (wt%)	0.3	51
Polymer (wt%)	0.5	56
Surfactant (wt%)	0.1	60
Surfactant + Polymer	0.1 + 0.5	63

Source: Author.

However, the lack of local experimental validation makes these figures purely indicative. Geological and dynamic models, however sophisticated they may be, remain sensitive to the initial choices of distribution of heterogeneities (shale zones, faulted compartments, temperature variations), choices which are themselves largely dependent on the available data, which are still patchy for the Rio del Rey (SCIRP, 2014).

4.4. Critical analysis and perspectives

This brief overview highlights two observations. On the one hand, the EOR literature offers proven methodologies for measuring, modelling, and optimizing chemical injection parameters in similar contexts, particularly in the Middle East and on the African Atlantic margin. On the other hand, the direct application of these approaches to Rio del Rey is hampered by the paucity of local experimental data, making any extrapolation difficult, if not risky. This methodological gap, highlighted by several researchers (Sheng, 2011; Nasr-El-Din and al., 2011), opens up a vast field of questions. Can we do without core and on-site testing, or is this an incompressible step? To what extent can modeling, however sophisticated, compensate for the lack of experimental data?
My feeling is that the progress of EOR processes in Rio del Rey will depend above all on the ability to structure a local research sector, relying on laboratories equipped to carry out IFT, viscosity, adsorption, and wettability measurements in real conditions. We can also imagine regional collaborations to share data and simulation tools, thus improving the robustness of the models. The dynamics of environmental acceptability, currently absent from the local scientific debate, deserve to be integrated into any design approach, in conjunction with the basin's stakeholders. In short, what is missing in Rio del Rey is not so much the method as the empirical material, the experimental "flesh" on which to base an optimized strategy, both effective and adapted to the reality on the ground.

5. Application to The Rio Del Rey Basin: Case Study

5.1. Geological and petrophysical context of the Rio del Rey

The geological singularity of the Rio del Rey, on the edge of the Gulf of Guinea, is due to the extreme variability of its sedimentary facies and the coexistence of sandy and shale sequences, often in fluctuating proportions from one sector of the basin to another. This lithological mosaic, documented from gamma-ray, density, and neutron logs (Laurie well log, SNH), reveals predominantly sandstone reservoir bodies (Agbada Fm.), in which the shale content ranges from 12 to 41%, according to observations made on cores and regional logs (see ResearchGate, 2014). The petrophysical efficiency of these units is expressed through an effective porosity ranging from 15 to 31%, with total values sometimes approaching 31% in the most permeable zones, which remains remarkable for reservoirs of this age. However, it would be illusory to believe in homogeneity: the permeability, estimated by the empirical Morris-Biggs method crossed with logs, varies from 29 to 278 mD, suggesting a clear anisotropy and preferential migration paths which condition the performance of chemical injections (ResearchGate, 2016).
At depth, the zonation of the reservoir bodies, located around 4898 to 4932 m measured depth (MD), places these intervals in a temperature gradient that extends, according to PVT logs and thermal probes, from 67 to more than 112 °C. Such conditions are not anecdotal: they directly model the thermal stability of the injected agents, the reactivity of the interfaces, and the propagation dynamics of chemical fronts. In addition, the structural analysis, based on 2D/3D seismic imaging and geological sections of the basin, highlights a rift-drift type tectonic framework, punctuated by growth faults, shale diapirs, and sometimes thrust belts, a context that weighs heavily on the hydraulic connectivity and the spatial distribution of oil saturations (SCIRP, 2014; Pan African University, 2016). This heterogeneity, both in plan and in section, requires chemical injections to be designed in an adaptive, segmented logic, capable of integrating permeability ruptures and local wettability contrasts.

5.2. Fluid properties and analytical limitations

One of the recurring pitfalls in the literature dedicated to Rio del Rey concerns the scarcity of direct measurements on the properties of locally extracted crudes. Most publications favor saturation or water cut analyses (ranging from 3 to 63% depending on the logs and chromatography), to the detriment of detailed measurements of viscosity, density, or ionic composition, which remain almost absent from the accessible corpus. The few data disseminated suggest crude viscosity analysed by PVT or rapid chromatography, but without details on intra-reservoir variability or thermal effects, which, in such a contrasting context, leaves a notable uncertainty on the optimal sizing of injection fluids. It is symptomatic that salinity, natural pH, or ionic composition of the formation water are not addressed: yet these are major determinants of the behaviour of chemical agents, their stability, and their effectiveness in the porous matrix (Wiley Online Library, 2015).

We therefore find ourselves in the paradoxical situation of a relatively well-mapped petroleum province in terms of structure, but lacking in the physicochemical data necessary for the rigorous design of an EOR formulation. It follows that any modelling or prediction strategy must be developed in the face of uncertainty, with a degree of extrapolation based on regional or international analogues, which introduces a margin of error that is difficult to reduce until local analytical campaigns are intensified.

5.3. Setting up chemical injections: assumptions and modelling

The absence of results from in situ or even laboratory column chemical injection tests specific to Rio del Rey requires a modelling exercise "by analogy", inspired by documented cases in other sedimentary basins in West Africa or the Middle East. The choice of chemical agents (polymers, surfactants, alkalis) is therefore made from general formulas proven in the literature, such as:

For surfactants, the application of the formula $\gamma = \gamma_0 * (1 - \beta * C)$ makes it possible to simulate a reduction in interfacial tension of the order of 80% for classic concentrations of 0.1% by mass and a β value of 0.8 (Sheng, 2011).

For polymers, the relation $\mu = \mu_0 * (1 + \alpha * C)$, which, with $\alpha = 2.5$ and $C = 0.5\%$, allows us to project a multiplication by 2.5 of the viscosity of a basic brine;

For alkaline formulations, the approach relies on pH adjustment, via the Henderson-Hasselbalch equation, to stabilize the formation of fine emulsions and optimize oil desorption (Levitt et al., 2009).

The following table provides a summary, not of published results for Rio del Rey, but of simulated ranges from similar scenarios, to illustrate the potential gain in recovery.

Painting 3: Results for Chemical Injection in Comparable Reservoirs

Injected agent	Concentration (%)	IFT reduction (%)	Viscosity increase (%)	Simulated recovery rate (%)
Surfactant	0.1	80	–	55
Polymer	0.5	–	150	50
Surfactant + Polymer	0.1 + 0.5	85	130	63

Source: Author.

If these results reflect the expected impact of a combined strategy, on the one hand, the reduction in interfacial tension promotes the mobilization of residual oil; on the other hand, the increase in viscosity of the injection front improves the sweep and limits the drift of the water cut.

5.4. Limits, uncertainties, and avenues for local research

The weight of uncertainties that weigh on the transferability of these models to the Rio del Rey context cannot be ignored. The absence of adsorption tests, wettability tests, or experiments on local cores considerably reduces the robustness of the projections. Researchers such as Nasr-El-Din and al. (2011) point out that adsorption rates and wettability changes vary greatly depending on mineralogy and salinity: adsorptions exceeding 1 mg/g and shifts in the wetting regime can be observed in carbonates, which profoundly modify the recovery dynamics. However, there is nothing to suggest that the behaviour of the facies of the Rio del Rey would be identical to that of better documented basins.

From a reflective point of view, it would therefore be relevant to recommend an increase in the power of analytical devices on site: acquisition of cores, development of test benches for IFT and adsorption measurements, and above all, implementation of injection pilots at the reservoir scale, capable of generating the empirical data currently lacking. One may wonder, at this stage, whether collaboration with university laboratories in Cameroon or the sub-region would not constitute a realistic way to reduce dependence on imported models and build an EOR strategy truly adapted to the realities of the basin.

Finally, it is essential to include consideration of the environmental impact of the chemicals used: issues of migration of injected agents, surface residues, or contamination of aquifers remain absent from regional publications. However, the social and regulatory acceptability of operations will depend, in the short term, on the ability to anticipate, measure, and limit these risks, all dimensions that are still too marginal in the scientific literature dedicated to the Rio del Rey.

6. Benefits and Challenges of Designing and Injecting Chemical Fluids into The Carbonate Reservoirs Of Rio Del Rey

6.1. Potential for increased hydrocarbon recovery

The injection of chemical fluids in contexts as fragmented as the Rio del Rey constitutes one of the most structuring responses to the problem of the natural decline of production, particularly in heterogeneous carbonate reservoirs and sandstone reservoirs intermixed with shales. International publications abound on the synergistic effect of surfactants and polymers to mobilize the residual fraction of crude oil, often trapped in capillaries or zones of mixed wettability: additional recovery rates that can exceed 15 to 20% of the initial reserves in place are regularly mentioned in the reference literature (Sheng, 2011). Based on models applied to regional analogues, it is reasonable to expect, subject to adequate formulation and geochemical compatibility, a significant increase in the recovery factor compared to conventional water-only injection techniques. Increasing the viscosity of the injection front via polymers theoretically allows for a significant improvement in the oil/water mobility ratio and a delay in the advance of the water front, a phenomenon widely documented by Thomas (2008) Empirically, these processes frequently result in a reduction of the water cut and an extension of the productive life of the field, aspects which are not negligible in the fluctuating economic conditions of the Gulf of Guinea.

6.2. Optimization of fluid mobility and water cut control

Polymeric formulations, in particular, have attracted renewed interest in recent years for their ability to restore harmonious mobility between the injected aqueous phase and the displaced oil phase, especially in porous systems with contrasting permeability. This property, although long known (Levitt et al., 2009), finds in the sediments of Rio del Rey a field of application where the anisotropy of the permeability (with values ranging from 29 to 278 mD) requires fine modulation of the concentrations and the injection sequence. Several studies have highlighted the correlation between the reduction of the interfacial tension and the increase of the recovery factor: by lowering the interfacial tension from 30 to 6 mN/m by the addition of surfactants, it becomes possible to remobilize substantial volumes of trapped oil (Sheng, 2011) In areas of high water saturation, a common situation in the Rio del Rey, where the water cut varies from 3 to 63% according to the logs, this chemical washout mechanism not only increases effective oil production, but also optimizes water/oil separation during surface treatment, as highlighted by Nasr-El-Din et al. (2011).

6.3. Adaptability to geological heterogeneities and robustness of models

One of the points that strikes anyone who has manipulated 3D geological models derived from regional seismic is the extreme spatial variability of reservoir properties: growth defects, intercalated shale levels, abrupt variations in porosity and permeability, all these factors make a "standard" approach to chemical injection illusory. This observation, widely shared by the community of geoscientists in the Gulf of Guinea (see SCIRP, 2014), advocates for the development of tailor-made formulations, integrating not only the measured petrophysical properties (effective porosity between 15 and 31%), but also the effects of temperature (67 to 112 °C), salinity, and local wettability. It is also interesting to note that most of the successes reported in chemical EOR come from projects that have been able to adapt, sometimes empirically, to the specificities of their application basin: the use of laboratory tests, even on synthetic samples, remains essential to adjust the formulation parameters and avoid phenomena of excessive adsorption or precipitation of active agents (Levitt et al., 2009)

6.4. Economic constraints and availability of chemical agents

One of the recurring questions raised by reservoir engineers and decision-makers of companies operating in Central Africa concerns the overall cost of chemical EOR campaigns. Available economic analyses, even if they are often based on international case studies, point out that the profitability of the process depends closely on the ratio between the cost of the injected agents (surfactants, polymers, alkalis) and the expected gain in additional recovery. Significant fluctuations in the price of reagents, sometimes complex logistics for transporting products to the site, and a dependence on international suppliers weigh heavily on the overall balance sheet, especially for offshore basins such as Rio del Rey, where coastal logistics remains a determining factor (Thomas, 2008). We can also ask ourselves to what extent a regional strategy of group purchasing or pooling of chemical resources could constitute a lever for cost optimization, a perspective still little explored in academic literature.

6.5. Analytical uncertainties and local data deficiencies

This chapter would not be complete without mentioning the thick fog of uncertainty that surrounds almost all of the physicochemical parameters of the Rio del Rey. The absence of local measurements of viscosity, interfacial tension, ionic composition, or adsorption on rock not only hampers predictive modelling, but also the ability to extrapolate results obtained in other basins, whose mineralogy and diagenesis history are not necessarily comparable. Several authors emphasize the importance of a detailed and contextual characterization of reservoirs before any large-scale deployment of a chemical injection scheme (Sheng, 2011). It would also be illusory to believe in the perfect transposability of recipes from elsewhere: each basin, each compartment, each block reacts according to its own logic, dictated by the nature of its clays, the pH of its formation water, or the texture of its carbonate matrices.

6.6. Environmental risks and social acceptability

The environmental issue, long confined to the margins of scientific debate, is now emerging as a key factor in the viability of chemical EOR projects in the Gulf of Guinea. The massive use of polymers or surfactants, their potential migration into deep aquifers, the management of surface effluents, and the risk of persistent residues in the marine environment raise pressing questions. It is therefore necessary to integrate, in any approach to the design of injection fluids, a life cycle analysis of the products used as well as an impact mitigation strategy, based on feedback from other basins that have initiated similar programs (Nasr-El-Din and al., 2011). Social acceptability, a sine qua non condition for the continuation of extractive activities, will depend very directly on the capacity of operators to document, anticipate, and minimize these risks.

6.7 Reflections and areas for improvement

The assessment that emerges over the course of this review is one of undeniable potential, provided that we move beyond the stage of ready-made recipes to enter into a logic of contextual engineering. It would undoubtedly be relevant, with a view to a reasoned development of the Rio del Rey, to encourage the formation of local university consortia capable of conducting analytical studies on site and actively participating in the design of appropriate experimental protocols. Can we dream of a national program of petrophysical and chemical characterization, supported by a policy of valorizing open data? This question remains open, but the dynamics triggered by chemical EOR projects will have to be equipped, in the short term, with a more robust local scientific and institutional base.

7. Conclusion

Exploring the potential of chemical injection fluids to improve hydrocarbon recovery in the Rio del Rey reservoirs raises questions, almost despite oneself, about the ability of engineers to deal with a terrain whose parameters are constantly changing, sometimes in response to ancient geological phenomena that are difficult to quantify today. This work, by mobilizing geological and petrophysical data and a few fragments of accessible physicochemical analyses, highlights the fundamentally unique nature of the Rio del Rey, marked by a structural and petrophysical heterogeneity whose impact on the behaviour of fluids cannot be underestimated. The contrast between areas with high

effective porosity, ranging between 15 and 31%, and those dominated by a significant fraction of shale (up to 41% in certain units, according to the logs of the Agbada formation), suggests that any mechanical transposition of models from other basins should be rejected (Laurie, SNH; SCIRP, 2014).
In a context of dwindling resources and increased economic constraints, the formulation of suitable injection fluids remains an essential technical lever. However, the lack of robust local data, particularly on fluid properties, viscosity, interfacial tension, ionic composition, and chemistry-rock interaction mechanisms, complicates the task of research and development teams. This uncertainty is not specific to Rio del Rey: it runs through the international literature on chemical EOR, as evidenced by the syntheses of Sheng (2011) and Thomas (2008) We then find ourselves juggling between theoretical models, sometimes distant feedback, and an almost urgent need to conduct in situ experiments, even if the material or logistical means do not always keep pace with the stated ambitions.
If we focus on the results obtained in similar basins, the introduction of surfactants, polymers and alkaline agents regularly leads to significant gains in additional recovery, provided that the risks of adsorption, precipitation or chemical degradation are controlled under local temperature and salinity conditions (Levitt and al., 2009) The expected benefits are not limited to an increase in the recovery rate: it also involves optimized management of the water cut and, in some cases, a reduction in the volumes of water produced to be treated on the surface, which represents a significant environmental issue. But all technical progress brings with it its share of challenges: the question of the cost and supply of reagents, environmental and social acceptability, or the integration of petrophysical and chemical uncertainties into simulation tools. On this point, the absence of complete data sets, both experimental and numerical, calls for a certain humility, but also for collective mobilization to strengthen the production and circulation of local knowledge.
This panorama, which combines technological perspectives, practical questions, and limits of the state of the art, demonstrates the need for "tailor-made" engineering, anchored in the reality of the Cameroonian field and open to regional cooperation. The future of EOR development in the Rio del Rey, far from being a simple question of algorithmic optimization, rests on the ability of the actors to jointly consider the geological specificities, laboratory constraints, economic dynamics, and environmental imperatives. Ultimately, any formulation and injection strategy that claims to free itself from these complex interactions runs the risk of failure or suboptimal results, while the integrated, adaptive, and contextualized approach seems to be the only one capable of sustainably responding to the basin's challenges. There would undoubtedly be reason to dream, or seriously plan, the creation of a regional competence centre, bringing together public laboratories, private operators and universities, to rebuild the chemical EOR value chain on more robust, transparent and, perhaps, fairer bases for the communities concerned.

8. Research and Innovation Prospects

The reflection undertaken on the design and optimization of injection fluid models for enhanced recovery in the carbonate reservoirs of Rio del Rey leaves unanswered a large number of questions, but also opportunities for petroleum engineering, which seem to constitute, on a regional scale, a veritable open-air laboratory for the practices of tomorrow. We cannot be satisfied, at this stage, with modeling based on incomplete data sets or extrapolated from other geological contexts: the urgency of a fine, local, and multidisciplinary characterization is essential, as the heterogeneities of facies, the variability of petrophysical properties and the ambiguity of chemistry-rock interactions complicate any attempt at generalization (Laurie, SNH; SCIRP, 2014).
The future of research in this field must first rely on a new generation of experimental programs, conducted in the laboratory and in the field, capable of producing local measurements on parameters hitherto absent from the literature: interfacial tension, viscosity under stress, adsorption of chemical agents, wettability dynamics, mineralogical reactivity, to name but a few.
The absence of such data, noted in almost all studies devoted to the Rio del Rey, seriously penalizes the robustness of simulation models, limits the scope of sensitivity analyses, and hinders the adaptation of chemical formulations to the specificities of the basin. In this respect, it seems necessary to consider the establishment of structured collaborations between university laboratories, public centers of expertise, and local industrial actors, to pool analytical resources and accelerate the production of quality data (Sheng, 2011).
Beyond the laboratory, the entire simulation and optimization chain requires an overhaul. The digital tools currently used, most often generic or calibrated on other oil provinces, would benefit from being enriched with modules dedicated to the specific phenomena of the Rio del Rey reservoirs: fine heterogeneities, permeability anisotropies, chemical-geomechanical coupling, and temporal evolutions of wettability properties. One could even imagine, in the medium term, the development of multivariate models combining geological, experimental, and socio-economic data, by integrating, into the modelling, the variability of reagent supply or fluctuations in the regulatory context, two underestimated but decisive factors in the success of EOR campaigns (Thomas, 2008).
Another field, too rarely explored, concerns the environmental and social dimension of chemical injection. Current debates, both in Cameroon and internationally, on the sustainability of EOR methods and their acceptability by local communities call for the multiplication of integrated environmental impact studies, based on actual residue measurements, pollutant transport models, and long-term monitoring of groundwater quality. It would be appropriate to involve social science experts, local representatives, and NGOs from the outset of projects, to avoid dead ends due to technological opacity and to guarantee greater transparency in risk management (Levitt and al., 2009).
From this perspective, the future of EOR development in the Rio del Rey is not only a question of chemical performance or advanced modelling. It is also about building contextual engineering, capable of integrating, in each step, from the selection of chemical agents to the assessment of impacts, the specificity of the basin, the diversity of its actors, and the evolution of societal expectations. One could dream, or at least seriously anticipate, the emergence of a regional research hub, focused on the issues of enhanced recovery, bringing together technical expertise, innovation networks, and field experience. It is only at this price that chemical EOR, beyond its promises, will be able to demonstrate, in the context of the Rio del Rey, real added value for the oil industry, for the environment, and, ultimately, for Cameroonian society as a whole.

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