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# Introductory Chapter: Developments in the Exploitation of Unconventional Hydrocarbon Reservoirs

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## 1. Introduction

Hydrocarbon reservoirs contain fossil fuels and constitute a major proportion of sources of energy worldwide. In the past, extraction of oil and gas was mainly restricted to conventional reservoirs which underlie a sealing caprock or rock formation with lower permeability and consist of rock and fluid with characteristics that readily allow the flow of oil and gas into wellbores. These reservoirs are easily assessed and contain sufficient pressure such that the external and additional drive necessary to push the hydrocarbon fluids to the surface are not exigent. Conventional reservoirs are recognised by their structural layout, stratification and rock and fluid properties. Typically, they comprise three major parts: a cap rock, a source rock and a reservoir rock. The cap rock is the impermeable rock layer that seals the boundaries of the top and sides and entraps the hydrocarbons within the reservoir. Hydrocarbons are formed in the source rock (normally limestones or shales) which contains kerogen, an insoluble and solid organic matter. The reservoir rock is the permeable and porous layer containing hydrocarbon fluids generated in the source rock. Over a protracted period, oil and gas formed in source rocks migrate to reservoir rocks, a process that is essential for the existence and validity of reservoir rocks.

With the advent in advanced technology and increasing need for more and cleaner energy, oil and gas production has been extended to unconventional reservoirs. Generally, unconventional reservoirs are difficult to produce. They are mainly composed of very tight source rocks containing hydrocarbons that have not migrated to reservoir rocks. These ultra-tight source rocks are termed unconventional reservoirs. Fundamentally, unconventional and conventional reservoirs are differentiated based on the migration of hydrocarbons from source rocks. Conventional reservoirs are rock formations that are recipient of hydrocarbons from source rocks, while unconventional reservoirs are source rocks containing hydrocarbons that cannot be naturally released to reservoir rocks. Nonetheless, the term unconventional reservoirs broadly cover reservoir rocks which are problematic to produce, for instance, tight reservoir rocks (tight sandstones, tight limestone, etc.) and heavy oil reservoir rocks.

Artificial lift is a standard method of instigating flow from the reservoir through the wellbore. This technique decreases the bottomhole pressure (BHP) while increasing the pressure in the reservoir, thereby raising the rate of well production. It is inevitably required at a certain time during the life of an oil/gas field due

| Themes |
| --- |
| i. Reservoir stimulation strategies |
| ii. Fracturing fluids and fluid systems |
| iii. Diffusion and mixing of fracturing and hydrocarbon fluids |
| iv. Well test analysis |
| v. Health, safety and the environment |

**Table 1.**
*Outline of some fundamental aspects of unconventional oil and gas production.*

to diminishing flow rates or for the removal of liquids to enable gas flow. Often, artificial lifts are sufficient for conventional reservoirs as a means of actuating or boosting flow; however, when applied in isolation, the same effects are not obtained in unconventional reservoirs. A vast amount of hydrocarbons are trapped within unconventional reservoirs. These reservoirs possess tremendous economic potential which can only be realised if they are properly stimulated. A range of reservoir stimulation methods are now available which have rendered unconventional reservoirs commercially viable. Some of these methods (e.g. hydraulic fracturing) can be applied to a broad spectrum of reservoirs, whereas others (e.g. some forms of acidisation) have limited applications. Since the boom in production from unconventional reservoirs, great strides in development have been made, with an increasing number of source rocks and depleted reservoir rocks subject to being produced. This has also raised concerns in relation to the impact on atmospheric, aquatic, land and underground environments; climate change; economic viability; technology requirements; health and safety; and sustainability. Ongoing studies are geared towards improving the process of exploiting unconventional reservoirs and increasing value for money while ensuring minimal levels of pollution and contamination to the environment, as well as risk to humans, and flora and fauna. The scope of areas considered in terms of the exploitation of unconventional resources is apparently inexhaustible, especially when viewed from a microscopic perspective. However, these can be harmonised into a more condensed list of themes. Some key aspects regarding the exploration and production of unconventional reservoirs are discussed in this chapter. These are encompassed within the subjects of discourse itemised in **Table 1**.

## 2. Reservoir stimulation strategies

Reservoir stimulation is simply described as the induction of formations to improve hydrocarbon production. This is can be accomplished by repairing the formation damage, especially at the vicinity of the wellbore, and/or changing the natural state of the rock or fluids to increase reservoir productivity. The advent in oil and gas production from unconventional reserves has given rise to the development of several stimulation approaches. This inventory (of methods) has expanded over the years, with considerable improvements made to boost the effectiveness and efficiency of a sizeable number of them. Some techniques are focused on repairing damages that have impaired the conductivity of rocks surrounding the wellbore, and some artificially create additional channels to enable easy flow of reservoir fluids towards the wellbore, while others alter the properties of reservoir fluids to make them less adhesive to host rocks and to encourage nonviscous-like fluid flow into wellbores. Numerous stimulation techniques are currently employed in

practice. These include hydraulic fracturing, surfactant flooding and treatment, water imbibition, acidisation, thermal stimulation and treatment and electrokinetics potential.

## 2.1 Hydraulic fracturing

Hydraulic fracturing is the artificial initiation and proliferation of fractures by high-pressured injection of fluid into the rock. The fracturing fluid is pumped into the rock at a pressure that surpasses the rock failure stress [1]. The operation is aimed at generating new fractures, reopening/expanding and extending the reach of existing fractures and increasing their connectivity. The concept of this well stimulation technique was foremostly introduced by Hubbert and Willis [2] and has since been developed into an effective and widely used method of increasing oil and gas reservoir productivity. Hydraulic fracturing has been successfully applied in various conventional (for enhanced oil recovery/gas recovery (EOR/EGR)) and unconventional reservoirs/source rocks, such as oil shales and tight rocks (i.e. tight oil/gas sandstones, limestones, shale, etc.) (e.g. [1, 3, 4]). Various designs of hydraulic fracturing operations are currently implemented in practice; an example is multicluster-multistage horizontal well fracturing (e.g. [5, 6]).

## 2.2 Surfactant treatment/flooding

Surfactant flooding is a technique used to lower the amount of oil entrapment in the rock matrix. Surfactants are amphiphilic organic chemicals comprising hydrophobic and hydrophilic compounds. When injected into ultra-low permeability hydrocarbons rocks, they reduce the oil viscosity, pore capillary forces and the interfacial tension between water and oil and decrease oil-wet wettability [7–9].

## 2.3 Thermal stimulation/treatment

Thermal stimulation and treatment are particularly useful for reservoirs with high-viscosity fluids and for the release of methane-rich gases from gas hydrates. Heavy oil formations contain high-density and high-viscosity fluids, which make them even more challenging to produce. Viscosity is heat dependent, having an inverse relationship with temperature. This implies that when there is a rise in temperature, the heavy reservoir oils become less viscous and, thus, more mobile. Thermal stimulation methods for heavy oils include steam flooding, steam-assisted gravity drainage (SAGD) and cyclic steam stimulation [10, 11]. Methane-rich gases naturally trapped in gas hydrates can be produced by raising the temperature of the formation. In practice, steam or hot brine is injected to heat the deposit; however, other innovative methods, e.g. microwave heating and electromagnetic heating, may be adopted [12].

## 2.4 Acidisation

This is the injection of acids into a reservoir to dissolve the rock matrix. Dissolution of portions of the rock creates wormholes while increasing its permeability and porosity [13]. Acid fracturing and matrix acidisation are the two main acidisation methods adopted as stimulation techniques [14]. The most commonly used types of acid are hydrochloric acid (HCL) and hydrofluoric acid (HF). These are often not applied singly; rather they are combined together or with other types of acids (e.g. organic acids) (e.g. [15, 16]). Carbonate rocks such as limestone,

dolomites and carbonate-rich shales are readily soluble in HCL. On the contrary, silicate or quartz-based rocks (e.g. sandstones) are not soluble in HCL; they react favourably with HF.

## 2.5 Water imbibition

This is the process of absorption of water as the wetting phase into rock, in which saturation by the wetting phase rises while that by the non-wetting phase reduces. This phenomenon can be induced by water flooding [17] or surfactant flooding [18, 19]. A shift in wettability from oil-wet to water-wet increases water imbibition. Water imbibition into porous rock improves oil recovery by displacing trapped hydrocarbons at both the rock surface and the pores. An example of this is *spontaneous imbibition* which is used successfully for oil recovery in shale reservoirs [20, 21].

## 2.6 Electrokinetics potential

Passing direct current (DC) through an oil reservoir generates an electrokinetics potential which causes electrophoresis, electromigration, electrochemical reaction, electro-osmosis and Joule heating [22]. The collective actions of these mechanisms improve formation rock permeability and porosity through the dislodgement and removal of pore linings in the form of colloids, thereby increasing pore sizes and creating new flow paths [22].

## 3. Fracturing fluids and fluid systems

Fracturing fluids are used for hydraulic fracturing and are injected into formations either as highly pressurised fluids or as acid-based fluids used to etch the walls of existing or newly formed fractures, creating additional flow channels. There are four main categories of fracturing fluids: water-based, oil-based, acid-based and foam-based fracturing fluids. The characteristics of fracturing fluids affect the pattern of fractures formed. Viscosity and density are the major properties that primarily determine the fluid behaviour. When designing a fracturing fluid system, it is imperative that, at least, the following are taken into consideration: fluid viscosity, fluid rheology, rock conductivity, cost, the impact on the environment, proppant carrying capacity, friction loss, compatibility of the fluid with the formation rock and the net pressure drop in the fractures.

The first type of fluids preferred for hydraulic fracturing was oil-based, including hydrocarbons such as gasoline and kerosene [23, 24]. Oil-based fracturing fluids are low in viscosity and generally need to be mixed with chemicals for its quality to be improved. They are excellent fracturing fluid alternatives for water-sensitive formations. Oil-based fluids are shown to be recyclable and compatible with drilling fluids and can be fully recovered during clean-up [25].

Water-based fluids are the most predominant fracturing fluids and in many ways better alternatives to oil-based fluids. The advent of water-based fracturing fluids introduced the petroleum industry to safer and cheaper substitutes to oil-based fluids. They can be classified as slickwater, cross-linked fluids, uncross-linked (linear) fluids and viscoelastic surfactant (VES) fluids [24]. Water-based fracturing fluids are aqueous, consisting mostly of water mixed with varying proportions of chemical additives and proppants [26]. The added chemicals may serve as viscosifiers or friction reducers. Acid-based fluids are suitable for formation rocks that are acid-soluble.

Acid-based fracturing fluids frequently used in practice are hydrochloric acid (HCL), hydrofluoric acid (HF) and organic acids. Carbonate rocks (e.g. limestone, dolostone and carbonate-rich shale) and silicate-rich rocks (e.g. sandstone) are soluble in HCL and HF, respectively [13, 27]. Most formation rocks are not exclusively one or the other; therefore, in many instances, an acid blend (mud acid) comprising a combination of more than one type of acid is used.

Foam-based fluids are composed of a mixture of gas and liquid phases with a very high percentage of the gas fraction within the range of $52\% \leq F^g \leq 96\%$, where $F^g$ is the percentage composition of gas [28]. Nitrogen ($N_2$) and carbon dioxide ($CO_2$) are the common gas phases used in practice, while either acids or water or polymer or alcohol (methanol) constitute the liquid phase [29]. Foam-based fluids are also appropriate for water-sensitive formations and have been successfully applied in shale gas reservoirs [29, 30]. The proppant carrying capacity of foam-based fluids greatly exceeds (by $\approx 85\%$) that of water-based fluids. Their application requires a considerably less amount of water, and there is less liquid to recover at the end of the fracturing operation. Moreover, foam is recyclable and reusable, implying a reduction in waste and cost [29, 30]. The demerits are mainly the high initial costs and logistic requirement and the decrease in viscosity in high temperatures [30].

## 4. Diffusion and mixing of fracturing and hydrocarbon reservoir fluids

Hydrocarbon reservoirs are often multicomponent and multiphase. This means that in their natural state, there are variations in composition of reservoir fluids, occurring longitudinally and/or vertically. Key drivers of changes in reservoir
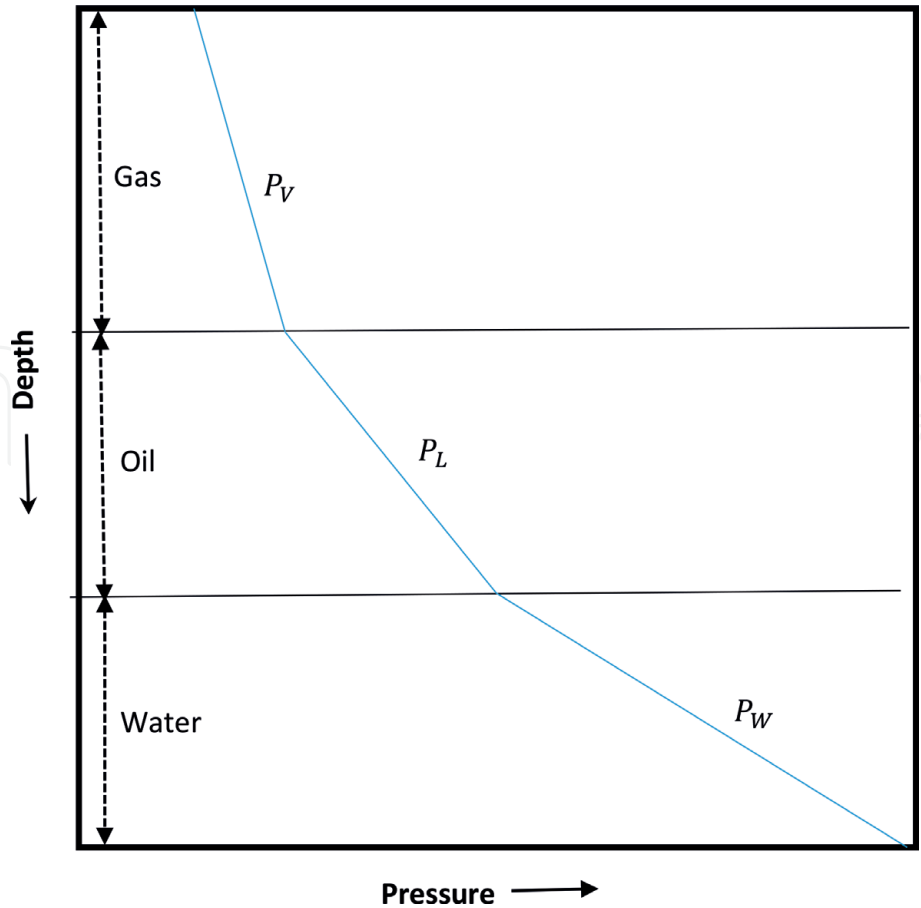


**Figure 1.**
*Pressure gradient of multicomponent reservoir fluids without capillary effect. P V, P L and P W are the vapour, liquid and water pressure, respectively [32].*

fluid composition are gravity, capillary forces and temperature gradients [31]. Gravity and capillary effects are major factors influencing variations in composition with depth ([32, 33]). Due to gravity, reservoir liquid hydrocarbons lie atop aquifers, which is a reflection of the differences in density between the two fluids (hydrocarbons are less dense and immiscible in water). In terms of hydrocarbons, the gas phase lies above the liquid phase, and their individual pressure gradient is dependent on their corresponding densities [32]. An idealised form of this, ignoring capillary effects, is shown in **Figure 1**.

Discounting capillary action renders the illustration in **Figure 1** unrealistic for formation rocks which are porous and therefore composed of pore spaces. Capillary forces due to surface tension within the pores act in opposition to external forces such as gravity. In addition, reservoirs are likely to contain a mixture of multi-component fluids at the different phases (gas and liquid), such as the occurrence of pockets of heavy hydrocarbons or injected fluids within the predominant fluid type. This will change the composition with depth in any or both of the following ways: firstly, capillary forces prompt the occurrence of a transition region, which is an overlap consisting of two or more phases instead of the sudden change shown in **Figure 1** and, secondly, the compositional gradient of the reservoir fluid is altered because of the changes in its components. A modified pressure gradient profile which also accounts for capillarity and compositional variation is given in **Figure 2**.
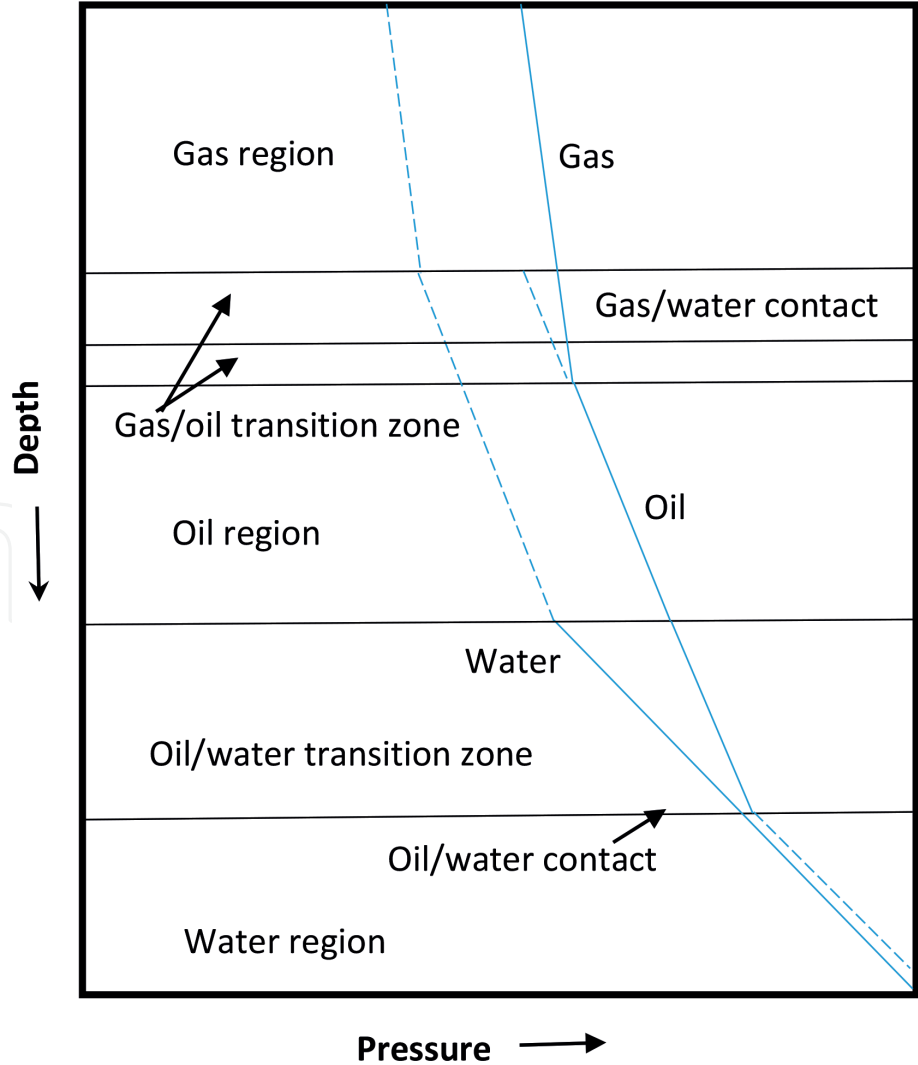


**Figure 2.**
*Pressure gradient of multicomponent reservoir fluid with the combined effects of gravity, capillarity and variation in composition [32].*

Temperature gradients in formations introduce an extra dimension to the behaviour of reservoir fluids. The effect of variations in temperature induces convection and thermal diffusion. For small temperature gradients collinear with the gravity vector, convection can be neglected [31]. Thermal diffusion, also known as 'Soret effect', is the separation of a non-convective mixture due to a thermal gradient [34]. In other words, there is movement of material during the occurrence of thermal gradients resulting in corresponding concentration gradients of the constituents of the fluid mixture. This process is measured by the thermal diffusion coefficient, $\alpha$. Thermal diffusion can have a substantial impact on variations in composition of reservoir fluids [34, 35]; it may increase or attenuate compositional variation vertically and horizontally.

The mixing of injected fracturing fluids with in situ and/or other fracturing fluids affects the constituent composition and variation of reservoir hydrocarbon fluids and the stimulation process during enhanced oil/gas recovery. The introduction of alien fluid(s) into the formation sets off a mixing mechanism and displacement of resident fluids, which improve hydrocarbon production. Controlling factors include, but not limited to, the injected/resident fluid properties (e.g. rheology, density and viscosity), formation rock properties, the reservoir condition (thermal gradient, pre-existing fluid compositional variation) and other drivers such as capillarity and diffusion. The practicability of this process involving a three-phase fluid system ($scCO_2$-brine-oil) is demonstrated in Jiménez-Martínez et al. [36], where supercritical $CO_2$ (as an injection fluid) is used to restimulate an oil-wet shale formation containing brine and hydrocarbon as the major resident fluids.

## 5. Well test analysis

Well test analysis—also known as pressure transient test analysis—consists of methods of finding and evaluating information regarding the well and reservoir. More specifically, it involves the manipulation and measurement of flow rates and pressures which can then be linked to well and reservoir conditions. The process primarily entails altering the well flow while monitoring temporal variations in pressure [37] or vice versa [38]. The magnitude and changes in pressure are used to deduce the reservoir size, wellbore damage, boundaries and heterogeneities (e.g. fault positions), reservoir pressure at the drainage region, well deliverability, flow rate [37] and other reservoirs or related parameters such as hydraulic connectivity, skin effect and permeability.

Well test analysis is the process of assessment and interpretation of data obtained from well tests using a variety of techniques. A diagnostic set of plots consisting of trends of pressure and its derivative (relating to time) against time is a common tool that facilitates the interpretation of well tests (pressure transient tests) [37]. The trend of pressure on these plots can then be used to determine the flow regime. For instance, flow regime *specialised* plots ($\Delta P$ *vs* $f(\Delta t)$) aid the identification of flow regimes [39] (e.g. radial, linear, bilinear and spherical flows), where $\Delta P$ is the change in pressure and $f(\Delta t)$ is a flow regime-specific function which is dependent on changes in time. An alternative approach (the Homer method) introduced by Homer [40] to overcome certain shortcomings of *specialised* plots measures $\Delta P$ against a superposition time specific to a given flow regime.

Over the years, the manner of conducting well test analysis has evolved. Types of well test analysis methods (interpretation methods) include straight line, pressure type curve and pressure derivative analysis and deconvolution; these are listed in order of the period they were developed. Detailed description of these methods is given in Gringarten [39].

## 6. Health, safety and the environment

Undoubtedly, the production of unconventional hydrocarbons is attendant with several benefits. These include an increase in the global quantity of energy sources, cheaper prices, the accessibility to relatively cleaner energies, etc. Despite these merits, there are various drawbacks subsumed under environmental impacts and health and safety. Occupational and public health risks are thriving in the oil and gas industry. While there are risk exposures common to hydrocarbon production in general, there are concerns specific to unconventional reservoirs. This can be viewed from three standpoints: the environmental impact, health and safety. Environmental effects deal with negative changes inflicted on the surroundings and far-reach zones (sub-surface, surface and atmospheric regions) as a result of production activities. Health and safety issues focus on the effect on humans and are divided into two facets: occupational and public.

### 6.1 Occupational health and safety

Workers are customary exposed to numerous hazards. Transport-related activities are reported as the highest cause of accidents due to the prolific movement of people, equipment, chemicals, hydrocarbon produce, etc. [41]. There is also a risk of explosions from inflammable and high-pressured fluids and contact with (by inhaling) hazardous constituent compounds of hydrocarbons such as hydrogen sulphide and crystalline silica usually used as proppants for hydraulic fracturing [41, 42].

### 6.2 Public health

A myriad of studies are available that support the narrative linking of unconventional hydrocarbon production with a range of human health problems. Examples of these effects are cancer, mental stress, eye irritation, respiratory disease, cardiovascular disease and congenital defects [43, 44]. Whereas the potential for these diseases is undoubted, evidence-based and scientifically proven cause-and-effect relationships between unconventional production activities and community health are lacking. The constraints, in some cases, are the inaccessibility to reliable data or the biased interpretation of data or the use of non-validated protocols to generate and analyse data. It is suggested that credible studies should be based on standard epidemiological procedures [43], which properly identifies stressors and their sources, the pathways through which humans are contacted and the health impact. Potential exposures include air, soil, surface water and groundwater contamination; odours; noise; seismic events and earthquakes; increase in traffic and accident rate; and water shortage [44].

### 6.3 Environmental effects

The impact of unconventional hydrocarbon production on the environment is principally focused on adverse alterations in the ecosystem, surrounding water bodies (e.g. aquifers and surface waters) and land and air contamination/pollution (such as greenhouse gas emissions). These can be categorised as air, land, water, biodiversity (ecosystems and wildlife) and waste impacts [45]. Air impacts involve emissions of volatile chemicals and greenhouse gases which reduce air quality, and waste impacts deal with challenges associated with the management of wastes produced by unconventional hydrocarbon production. Human exposures are facilitated through contact with affected media (i.e. air, land, water, biodiversity and waste).

## 7. Summary comments

Stimulation of unconventional hydrocarbon reservoirs to enable or improve production is inexorable. There are a plurality of reasons for this; the primary ones are encapsulated in the constraints that hinder the access of the target reservoir and/or source rock and the peculiarity of both formation rocks and fluids. The distinctive nature of unconventional formations are manifested through, for instance, rocks with ultra-low permeability and porosity, the presence of heavy oils as constituent reservoir fluids and the multiphase and multicomponent composition of the formation. Stimulation approaches used in practice are wide ranging. Some of these—e.g. hydraulic fracturing—are age long and have evolved into well-developed methods, whereas others, e.g. spontaneous imbibition, are advancing at a fast pace.

Hydraulic fracturing is traditionally used to artificially create additional flow channels by injecting fluids at high pressures; however, aspects of these techniques are adopted or used in tandem with other stimulation methods. Acid fracturing, for example, is one of the two major acidisation techniques and involves the injection of acids at pressures high enough to generate fractures while dissolving and etching their surfaces. The central objectives of each stimulation method and its limitation are determinants of the choice of fracturing fluid or fluid system. Obviously, it is expected that acid-based fluids would be used for acid fracturing operations. Likewise, either foam-based or oil-based fracturing fluids are superior options for water-sensitive formations. The behaviour of in situ reservoir fluids including their interactions with injected fluids (in terms of mixing, diffusion, etc.) influences the effectiveness of the recovery process and the recyclability and reusability of the introduced fluids. Pivotal drivers of reservoir fluid behaviour include the properties of the injected/resident fluid and formation rock, the reservoir condition, gravity, capillarity and diffusion.

Other important aspects regarding the exploitation of unconventional hydrocarbon formations are health, safety and the environmental effect. This is generally considered in terms of occupational and public health and safety and the environmental impact of drilling and production activities. Studies on occupational health and safety are fairly established; there seem to be sufficient evidence to substantiate correlations linking health and safety hazards with incidences of accident in the industry. Also, standardised environmental impact assessments have made it possible to identify and measure changes in surrounding and far-reach areas through, for instance, the use of indicators. Conversely, there are several grey areas with respect to threats to public health and safety, since the validity of many investigative studies is disputable because they are apparently subjective, incredible and therefore inconclusive.

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