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ARISTOTLE UNIVERSITY OF THESSALONIKI
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DEPARTMENT OF MINERALOGY – PETROLOGY – ECONOMIC GEOLOGY

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Fishbone wells. Drilling, stimulation and productivity

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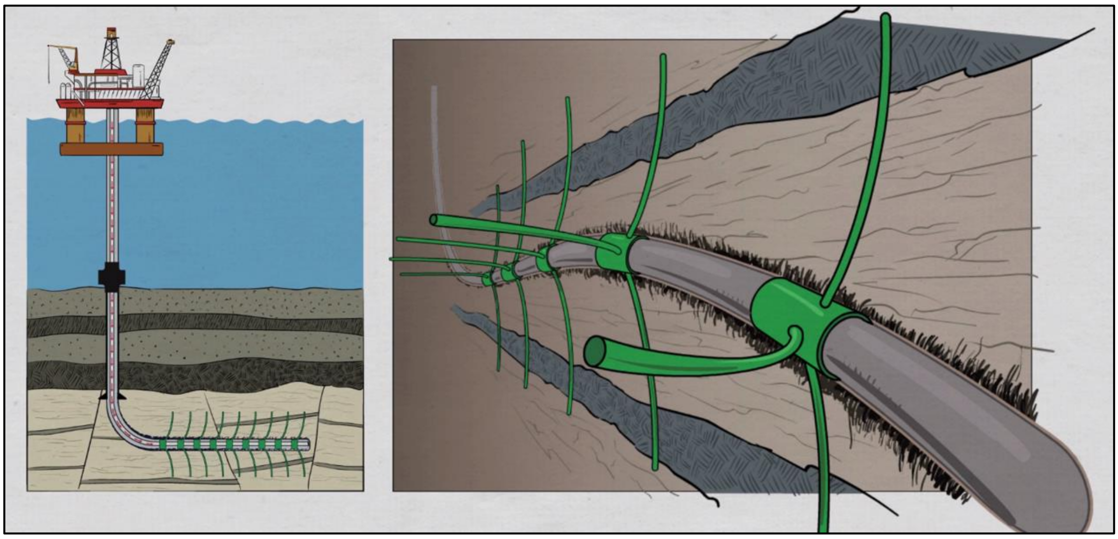

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Fishbone wells. Drilling, stimulation and productivity
Γεωτρήσεις τύπου fishbone. Όρυξη, διέγερση και παραγωγικότητα

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This dissertation was submitted in partial fulfillment of the inter-Institutional MSc Program "Hydrocarbon Exploration and Exploitation", offered by the department of Geology of the Aristotle University of Thessaloniki, in collaboration with the School of Mining and Metallurgical Engineering of the National Technical University of Athens, the department of Economics of the Democritus University of Thrace, and the Faculty of Geology and Geoenvironment of the National and Kapodistrian University of Athens. It represents 20 E.C.T.S. out of the total 30 of the fourth semester and its completion is mandatory for every postgraduate student.

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ABSTRACT

The aim of the present postgraduate dissertation is to study the process of drilling fishbone wells and the parameters that affect their performance. Drilling wells with multiple laterals has flourished in recent years as it is accompanied by many economic and environmental benefits. Fishbone wells are a subcategory of these, which aim to exploit the same reservoir layer through laterals extending from a central horizontal well. They stand out from the method of fishbone stimulation in terms of the radius of influence and the drilling procedure. For large-scale fishbone drilling, rotary steerable systems are primarily used due to the smoother wells that they are capable of drilling and secondarily the mud motors, with the trickiest part being the drilling of every kick-off interval, while the fishbone stimulation method follows a standard procedure, in which drilling mud is injected into a wellbore causing short laterals to extend, penetrating the reservoir around it. As for the productivity of the larger wells, it depends on the number of laterals, the angle they form with the main well and their geometry as it has been suggested that straight laterals have a greater inflow. Their length, distance, and scattering do have an impact, but it is not significant. There is disagreement as to whether these factors affect the initial transient period or the entire life of a reservoir. In addition, the role of the horizontal to vertical permeability factor is controversial. Due to their complex structure, the use of artificial intelligence and statistical methods to predict their production has begun.

Keywords: fishbone wells, fishbone stimulation, fishbone drilling, steerable motors, rotary steerable systems, productivity of fishbone wells

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ΠΕΡΙΛΗΨΗ

Στόχος της παρούσας μεταπτυχιακής διατριβής είναι η μελέτη της διαδικασίας διάνοιξης γεωτρήσεων τύπου fishbone και των παραμέτρων που επηρεάζουν την απόδοσή τους. Η όρυξη γεωτρήσεων πολλαπλών κλάδων έχει ανθίσει τα τελευταία χρόνια καθώς συνοδεύεται από πολλά οικονομικά και περιβαλλοντικά οφέλη. Οι γεωτρήσεις τύπου fishbone αποτελούν μια υποκατηγορία αυτών, που στοχεύουν στην εκμετάλλευση του ίδιου στρώματος ταμιευτήρα μέσω πλευρικών γεωτρήσεων οι οποίες ξεκινούν από ένα κεντρικό οριζόντιο τμήμα. Ξεχωρίζουν από τη μέθοδο διέγερσης, η οποία περιλαμβάνει γεωτρήσεις ίδιου σχήματος, ως προς την ακτίνα επιρροής και τη διαδικασία διάτρησης. Για μεγάλης κλίμακας τέτοιων γεωτρήσεων χρησιμοποιούνται κυρίως περιστρεφόμενα κατευθυνόμενα συστήματα (rotary steerable systems) λόγω των ομαλότερων γεωτρήσεων που μπορούν να διανοίξουν και δευτερευόντως οι κινητήρες λάσπης (mud motors), με το πιο δύσκολο κομμάτι να είναι οι διάτρηση του εναρκτήριου διαστήματος κάθε πλευρικού κλάδου, ενώ στη μέθοδο διέγερσης ακολουθείται μια τυπική διαδικασία κατά την οποία διατρητική λάσπη εισπιέζεται σε μια γεώτρηση προκαλώντας την έκταση των κοντών πλευρικών κλάδων, διεισδύοντας στον ταμιευτήρα γύρω της. Όσον αφορά την παραγωγικότητα των μεγαλύτερων γεωτρήσεων, αυτή εξαρτάται από τον αριθμό των πλευρικών γεωτρήσεων, τη γωνία που σχηματίζουν με την κύρια γεώτρηση και τη γεωμετρία τους, καθώς έχει προταθεί ότι οι ευθύγραμμοι κλάδοι έχουν μεγαλύτερη εισροή. Το μήκος, η απόσταση και η διασπορά τους έχουν αντίκτυπο, αλλά δεν είναι σημαντικός. Υπάρχει διαφωνία ως προς το εάν αυτοί οι παράγοντες επηρεάζουν την αρχική μεταβατική περίοδο ή ολόκληρη τη διάρκεια ζωής ενός ταμιευτήρα. Επιπλέον, ο ρόλος του παράγοντα της οριζόντιας προς κατακόρυφης διαπερατότητας είναι αμφιλεγόμενος. Λόγω της πολύπλοκης δομής των γεωτρήσεων τύπου fishbone, έχει ξεκινήσει η χρήση τεχνητής νοημοσύνης και στατιστικών μεθόδων για την πρόβλεψη της παραγωγής τους.

Λέξεις-κλειδιά: γεωτρήσεις τύπου fishbone, διέγερση ταμιευτήρα με γεωτρήσεις τύπου fishbone, διάτρηση γεωτρήσεων τύπου fishbone, κατευθυνόμενοι κινητήρες γεώτρησης, περιστρεφόμενα κατευθυνόμενα συστήματα διάνοιξης γεωτρήσεων, παραγωγικότητα γεωτρήσεων τύπου fishbone

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1. Introduction

1.1 The prevailing situation in hydrocarbon exploration and production

The oil and gas industry is always in demand of more efficient methods of drilling and stimulation (Freyer et al., 2009). This situation, combined with the ongoing shift of the world towards environmental sustainability in terms of the impact of human activities, and the fact that many reservoirs extend laterally more than they do vertically, has intensified the search for more efficient ways of drilling (Durst et al., 2012). Technological advancement provided the industry with an alternative way of exploitation, that of multilateral wells (Xiance et al., 2009). Fishbone wells is a sub-category of those (Xiance et al., 2009; Al-Rbeawi & Artun, 2019). Their use not only contributes to the reduction of the environmental impact of hydrocarbon exploitation but also enhances the production and ultimately increases the reservoir's recovery factor (Bone et al., 2016), especially from reservoirs with low permeability (Xiance et al., 2009). But it is necessary for both the drilling tools and the methods used to be sufficient to drill wells with complex trajectories (Voronin et al., 2019). High quality geological and geophysical interpretation is also an essential service while drilling within these complex fields, therefore the method of logging while drilling is used to deliver a wide range of measurements (Abaltusov et al., 2019). Since horizontal wells may have a variety of different configurations, the analysis of their production at every flow regime can be very challenging (Ayokunle & Hashem, 2016). Despite all the above, the need for reservoir stimulation is still present, but the application of the classical stimulation methods is accompanied by their drawbacks (Xiance et al., 2009). The solution may be a newly developed stimulation method involving small-scale fishbone wells.

1.2 Aim of this study

The objective of this thesis is firstly to inform about the fishbone well type and, secondly, to present the most decisive factors that affect the productivity indices of these wells, and the recent methods through which the optimal configuration can be determined.

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2. The applications of wells of complex structure and geometry

2.1 Resources and reserves

2.1.1 Grouping criteria and characterization

According to the revised version of the Petroleum Resources Management System which was released in June 2018, the distinction between reserves and resources is based on some key factors. From a geological perspective, an important role plays the risk of discovery. From the technical aspect, the feasibility of the project is taken into consideration along with the existence of the technology needed. The final factor is the commerciality of the project which derives from various economic, social, and legal criteria.

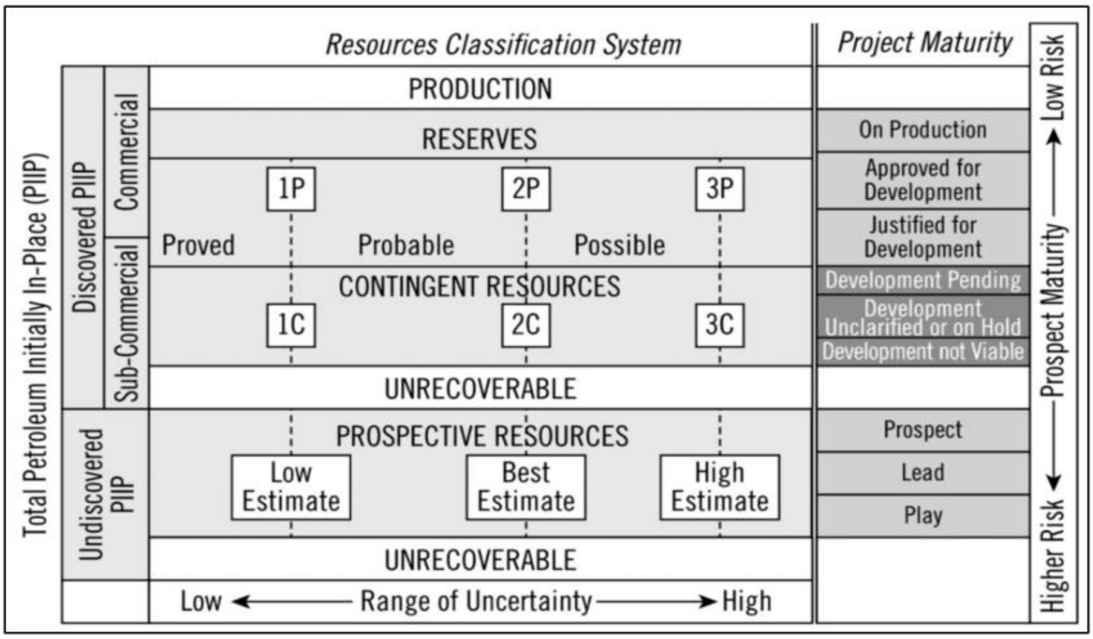

Figure 1: *The hydrocarbon resources classification system of Petroleum Resources Management System, published by the Society of Petroleum Engineers Oil and Gas Reserves Committee. (Canbaz et al., 2020)*

Petroleum is a naturally occurring compound of hydrocarbons and non-hydrocarbon content. The hydrocarbons may be in the gaseous, liquid, or solid state. Commonly occurring non-hydrocarbon compounds is carbon dioxide, nitrogen, and hydrogen sulfide.

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The term "resources" is an alternate expression to the Total Petroleum Initially-In-Place (PIIP), and, as it is illustrated in Figure 1, it represents the summary of all quantities that are assessed to exist in every accumulation in nature, both discovered and undiscovered. The term includes petroleum in both conventional and unconventional reservoirs, whether it can be recovered from them or not. Already produced quantities are also taken into consideration in the total petroleum summary.

Resources are then categorized into discovered and undiscovered based on the existence of tangible evidence of significant oil and gas though exploratory wells. Discovered resources are considered a) the already produced quantities, b) the reserves which are all the accumulations that are anticipated to be recovered in the near future with the current technological means, c) the contingent resources which are potentially recoverable quantities should better circumstances allow for their exploitation, and d) the unrecoverable portion which may be classified as recoverable in the future if commercial, technological or explorational circumstances change. The value that represents the total undiscovered resources is an estimation of quantities that may be trapped in the Earth's crust but are yet to be discovered. Those resources are divided into two categories. The first category is the prospective resources which are accumulations that may be recovered if geologic discovery is finally made and the complexity of the environment is manageable by the current technological stage, and the second category is the unrecoverable portion of the currently undiscovered resources.

2.1.2 Essential components and differences of petroleum systems

Depending on the properties of both the reservoir and the hydrocarbons it accommodates, a petroleum system may be classified as conventional or unconventional.

Conventional characterization indicates that the fluids can flow naturally from the porous and permeable rock to the well and be produced in economically sustainable quantities without any major stimulation treatments. The hydrocarbons are trapped in discrete areas where favorable geological conditions are present. At its initial stage, the system is in hydrostatic equilibrium and each fluid phase is separated by a well-defined inner contract surface. The three types of these surfaces are the Oil-Water Contact (OWC) inner surface between the liquid hydrocarbons which buoy on the underneath water body, the Gas-Oil Contact (GOC) which exist between the liquid and the gaseous hydrocarbons, and the Gas-Water Contact (GWC) which is present in gas reservoirs where liquid hydrocarbons are absent.

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The key elements of a conventional petroleum system are 1) the source rock, 2) the reservoir, 3) the geological trap, 4) the seal rock, 5) sufficient quantities allowing for commerciality, 6) maturation of petroleum though time and temperature, 7) the migration path from the source rock to reservoir, and 8) the dominant mechanism to drive production.

On the other hand, unconventional resources are governed by low permeability porous media and/or high fluid viscosity, hence traditional recovery methods such as through completely vertical wells are not applicable. These reservoirs require extensive stimulation such as hydraulic fracture and multilateral or horizontal drilling in order to produce at economically sustainable rates and reach a satisfactory recovery factor. The hydrocarbons are spread across a wide area and there is also no distinct separation of the fluid phases. In cases of hydrocarbons with a low API gravity, extra processing before the sale may be required.

When investigating a non-conventional petroleum system, it is important to keep in mind that some key elements of the conventional systems may be different, identical, or completely missing. For instance, shale is at the same time the source rock, the reservoir, the seal, and the trap, while investigating the drive mechanism is replaced by the process of identifying the shale's characteristics such as natural fractures.

The stage of development also differs for each type of petroleum system. At conventional systems, the process begins with an exploratory well to confirm the existence of the play, followed by an appraisal well to verify that the amount of oil in place enables commercialization, and to also delimit the accumulations. Finally, the necessary well completions are made, and production begins. On the contrary, during the development phase of an unconventional system, a great deal of effort is made upon identifying 'sweet spots' of the wide area that these systems expand to, and any naturally occurring fracture patterns. The exploration is continued with a transitional stage where various drilling, completion, and stimulation approaches are tested to confirm commerciality and optimize production plan. Then the production period follows in which drilling and fracturing operations are present throughout the life of the field. Expenses for multiple drill sites and frequent stimulation operations accounts for a major portion of the total operation cost. Any attempts to explore and mainly develop an unconventional system using conventional processes will most likely be disastrous. Discovering these reservoirs is not the hard part, but rather drilling wells that can maintain high productivity (Xiance et al., 2009).

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2.1.3 The reasons that led to the US shale boom

The estimated shale gas resources that can be technically recovered accounts for a substantial amount of the world's total gas reserves, however, as it is illustrated in Figure 2, they require advanced exploitation techniques and, as a result, there must be a safe margin of profit to amortize the cost. The United States have a long history of exploiting unconventional resources, especially shale gas. Within 11 years, from 2004 to 2015, its shale gas production increased from just 5% to 56% (Zeid & Lee, 2016). Improvements in directional drilling and hydraulic fracturing have increased single-well production in their shale-gas producing regions. The continuous involvement and experience of the service companies upon these processes have led to increased accuracy and reduction of operational time and cost. The most important technological advancements that allowed for the development of the unconventional sector are:

- The development of rock cracking methods.
- The multilateral drilling technique.
- Creation and evolution of 3D geosteering systems with Logging-While-Drilling (LWD) feature including real-time inclination and azimuth measurements.
- Utilization of the appropriate drill bit that best corresponds to each type of drill motor.

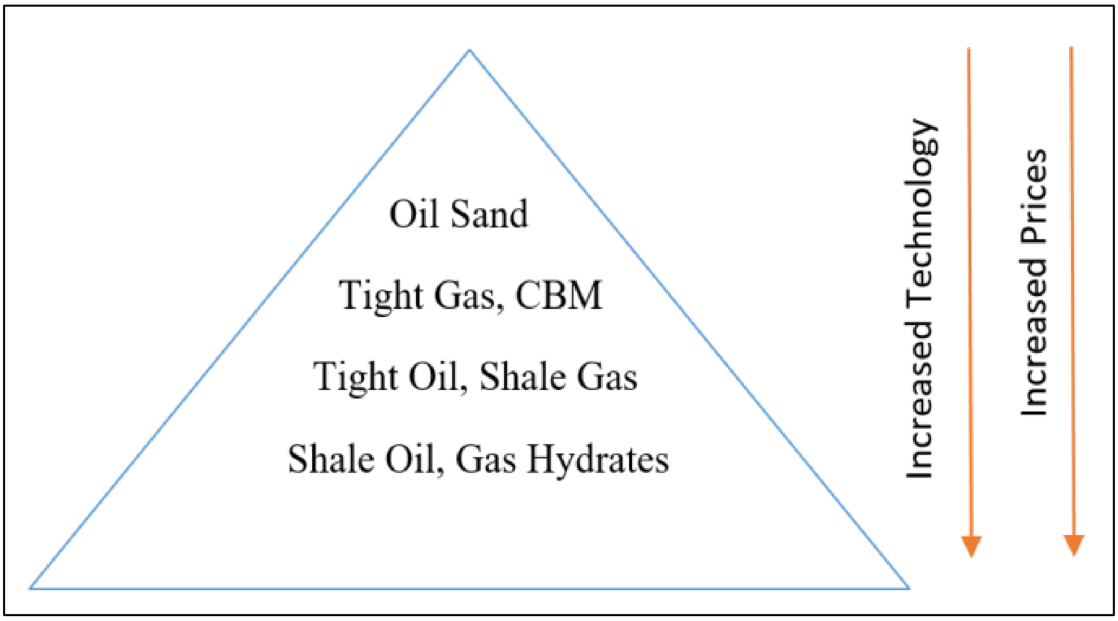

Figure 2: *Comparison of types of non-conventional resources based on the required technological advancement and costs for their extraction. (Canbaz et al., 2020)*

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The considerable amounts of shale hydrocarbons that exist outside the USA are gradually transitioning to the technically recoverable resources category. These natural resources are expected to represent a significant portion of the world's energy supply (Xiance et al., 2009).

2.1.4 The environmental impact of shale gas exploitation

The biggest concern of producing from unconventional reservoirs is the extensive water usage both for drilling and for fracturing, with the latter accounting for the biggest part. During fracturing, around 90% of the volume used is water, 9.5% is sand, and the remaining 0.5% consist of over 700 different chemicals. On average, each well require approximately 3-7 million gallons of water and 150,000 to 450,000 gallons of chemicals. The chemicals contribute to a successful fracturing outcome, reduce friction, and protect the well's integrity. Nevertheless, concerns are raised about possible groundwater contamination. In cases where the availability of water is limited, the use of large volumes leads to rapid depletion of local aquifers which in turn may bring society against the project as both the quality of drinking water and the quantities available for agricultural use are reduced. To address these issues, service companies are adopting measures such as optimizing wells to limit the runoff and disclosing the types of chemicals they use. Gradually, investments are made in ways of reusing or purifying water.

Some other major issues are the induced seismicity caused by fracturing the rocks, the great land use by the numerous wells, and the environmental pollution that upstream operations at each of these well causes. All the above contradict the companies' policies on minimum environmental footprint and represent challenges that they must overcome.

2.2 Multilaterals and the TAML classification system

2.2.1 Characterization of a multilateral well

A multilateral (or multi-branched) well consists of a main vertical borehole and at least one horizontal branch deriving from and connecting to it. This method of drilling is applicable to both onshore and offshore. The word "multilateral" may be used to address both the main wellbore as well as each of the laterals individually.

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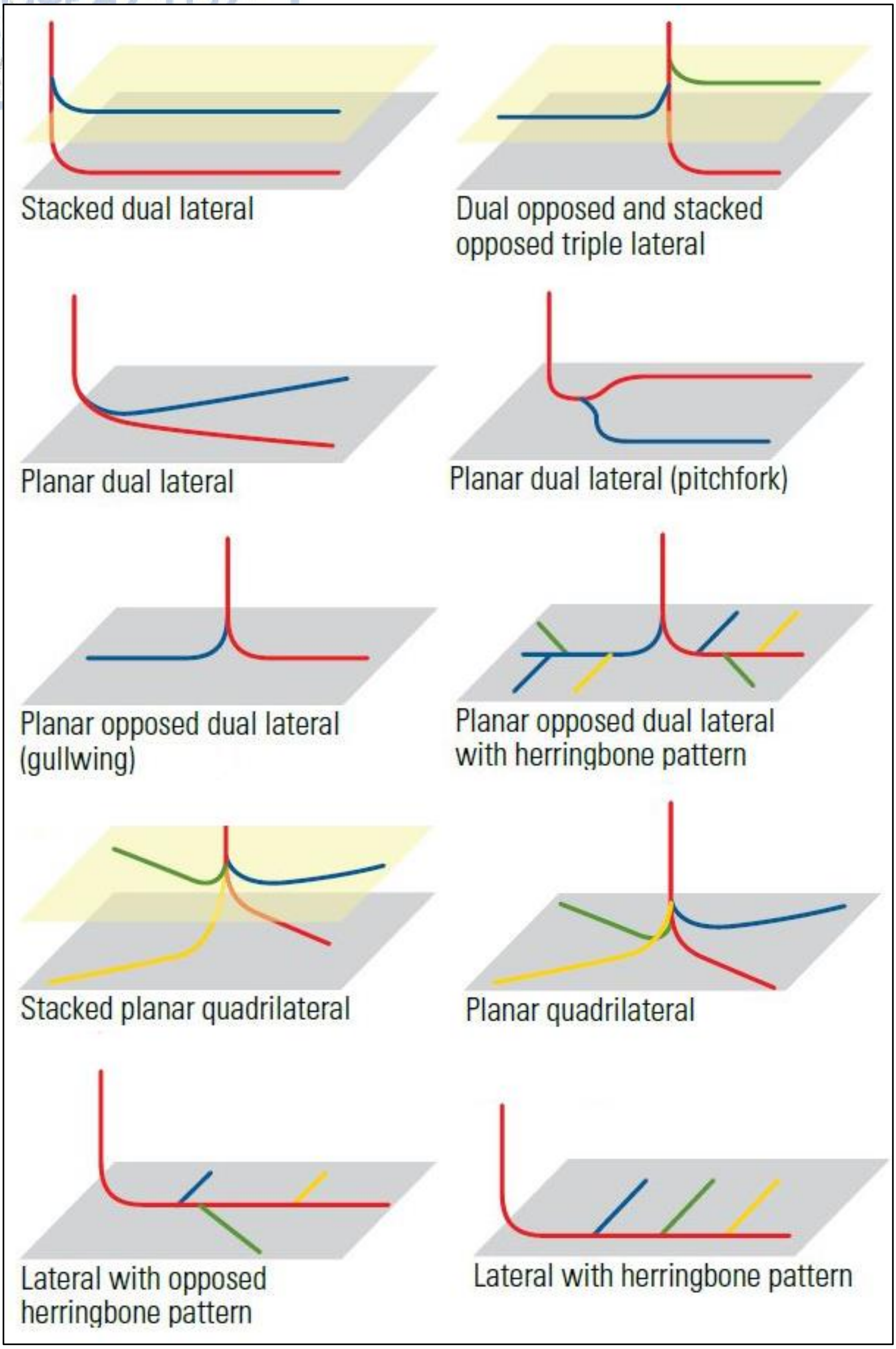

Figure 3: *Schematic representation of the various types of multilateral wells.*

(www.slb.com/resource-library/oilfield-review/defining-series/defining-multilateral-wells)

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The various configurations can be categorized into two general types: wells with vertically stacked laterals and wells with horizontally spread laterals. In addition to the shape itself, this distinction is complemented by the target scope of each type.

Vertically stacked lateral usually targets different pay zones in the vertical plane, thus eliminating the need for a dedicated vertical well for each horizon. Hydrocarbons from each layer can reach the surface by flowing in a shared production tubing, or every layer may have its own. Horizontally spread laterals commonly target the same reservoir interval. Their objective is to improve hydrocarbon production and maximize the recovery factor of that zone by enlarging the drainage area.

2.2.2 Types of multilaterals

As shown in Figure 3, the combination of laterals spread on the same horizontal plane with those placed on the same vertical plane can lead to wells, each having its own unique geometry. Therefore, the shape of a well is determined by the relative position of each hydrocarbon accumulation eligible for production and the extent of penetration needed to produce at an economically viable rate.

2.2.3 Advantages and disadvantages of multilaterals

The multilateral drilling method is a logical continuation of drilling multiple vertical wells that target the same or nearby pay zones within a generally small area. It is usually applied in a geologically puzzling environment and for the exploitation of unconventional resources (Abdulazeem & Alnuaim, 2016). The shift towards this method is justified by the great advantages which can be summarized as follows:

- Penetrating through a reservoir's overburden layers can be very challenging, (Rylance et al., 2020) especially in areas with an abnormal pressure gradient, extensive presence of aquifers, swelling clays and unconsolidated formations causing compromised wellbore stability so additional measures are required, such as more frequent casing and differentiation of the mud weight. Drilling a single vertical wellbore with horizontal sections deriving from it means that the risk associated with the above situations is being undertaken only once.

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- Greater reservoir exposure and connectivity between different networks of natural fractures lead to higher productivity index per vertical well and increased recovery factor of the target zones (Bone et al., 2016; Rylance et al., 2020). Moreover, accumulations previously characterized as uneconomic can be connected through laterals to form an economically viable well (Rylance et al., 2020).
- Equally distributed and reduced drawdown pressure combined with mitigated early gas and water breakthrough extend the life of a multilateral well (Rylance et al., 2020) while reducing the cost of extra drilling procedures that would have been needed in the case of single vertical or horizontal wells.
- The construction and placement of limited numbers of rigs and production trees has a positive impact on the capital expenditure and operation cost and restricts intervention in the environment (Rylance et al., 2020). Especially in cases of deep-water subsea prospects, drilling multilaterals is the key factor for the transition of the project to the development phase, otherwise impossible if multiple vertical wells were to be drilled. Ultimately, the cost of sealing on abandonment is significantly lower.

Although these wells have many advantages, it is important to mention the adverse factors that may ultimately prevent the selection of this type of wells. These are:

- The higher cost of installation compared to wells with a simpler structure.
- The higher risk associated with the complex methods used at drilling, completion, and production phases. This includes placing and removing tools as well as controlling the penetration of sand both in the main horizontal section if it is completed as an open-hole, and in the laterals which are usually not cased (Paiaman et al., 2009).
- The challenges that may arise during a stimulation workflow.

2.2.4 Technology Advancement of Multilaterals (TAML)

Since 1950, the use of multi-branched wells began to grow. By 1997, their layout had come to a stage of being quite diverse, so companies created a collaborative community - the "Technology Advancement of Multilaterals" (TAML) - and developed a common categorization framework. The primary classification criterion was decided to be the type of junction used to connect the main well to a lateral, which implies that they were categorized according to their complexity and functionality. The type of junction also suggests the isolation

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capabilities of a lateral and the subsequent accessibility to it. Six standards were created, namely TAML Level 1 to 6 (Figures 4 & 5).

As the level increases, so do the hydraulic isolation of the lateral, the cost of installation, and the risk associated with the complexity of the junction. In fact, the main risk related to multilateral wells is constructing and completing the junction rather than drilling the lateral itself. The logic of risk aversion is reflected in the type of wells that had been drilled until 1999, 95% of which were either level 1 or 2. Nonetheless, developing a field with multilaterals that host high-level junctions can be way more profitable than performing rig up from scratch to target different accumulations, especially in an offshore environment.

TAML Level 1

TAML level 1 well type indicates that the main hole, the lateral, and their junction remain uncased. To avoid wellbore collapses, this type is highly recommended for application only in consolidated formations. The main advantage of the level 1 type lies in the fact of low drilling and completion costs. However, the drawbacks are the inability to re-enter and the impossibility of controlling or separate the flow from the lateral.

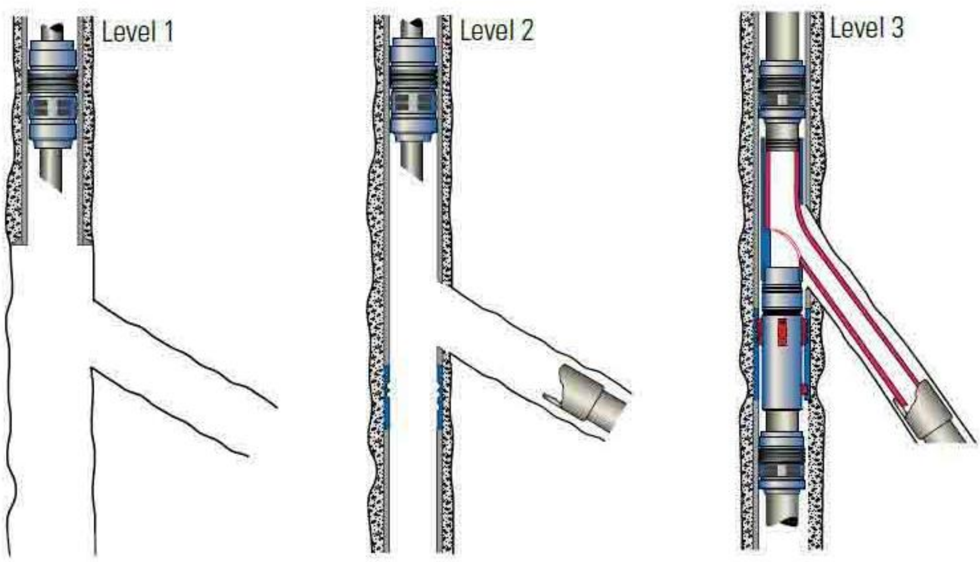

Figure 4: *Schematic illustration of levels 1, 2, and 3 of the TAML classification system.*

(www.slb.com/resource-library/oilfield-review/defining-series/defining-multilateral-wells)

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TAML Level 2

At a level 2 well, the main hole is cased and cemented while the laterals remain opened-hole. Cement limits the chances of the main wellbore collapsing. Usage of sliding sleeves and packers can provide the ability of zone-specific, or combined production.

TAML Level 3

Open-hole laterals that host a screened or slotted liner that is mechanically connected to the case of a cemented main bore indicate a level 3 well. This type consists of a relatively low-cost completion with re-entry capabilities. Therefore, the laterals are better supported than that of levels 1 and 2, and similarly, sliding sleeves and packer plugs can be used to control the production. But still, there is no hydraulic isolation of the lateral, and the application is best suited to consolidated formations.

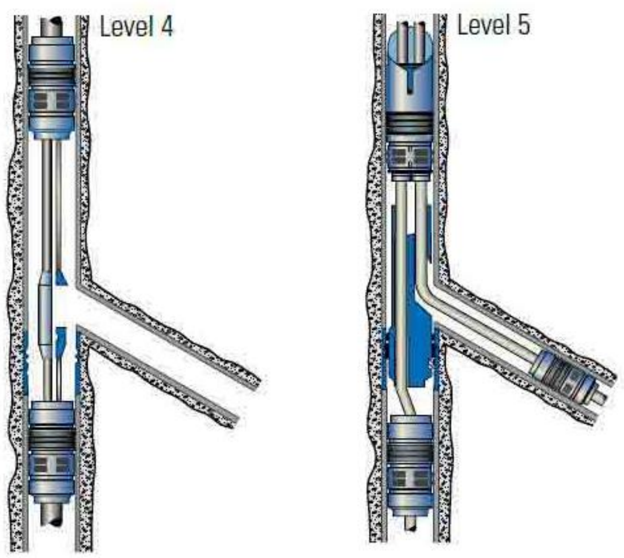

Figure 5: *Schematic illustration of levels 4, 5, and 6 of the TAML classification system (www.slb.com/resource-library/oilfield-review/defining-series/defining-multilateral-wells)*

TAML Level 4

At a level 4 well, both the main bore and the laterals are cemented at the junction, which expands the application to unconsolidated formations. Due to the weakness of cement against high differential pressure, the junction does not provide hydraulic isolation. However, it does

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provide full access to the main bore and lateral. There is also extensive mechanical support of the junction system.

TAML Level 5

Extensive completion equipment used at a level 5 well causes the junction with a lateral to be isolated from hydraulic pressure. The equipment includes packers and production tubing. One packer is placed inside the lateral and another at the main wellbore, below the junction point. Their connection to the dual string packer placed above the junction area is established by production tubing. This configuration allows for the adoption of a lower-level junction, excluding the lowest.

TAML Level 6

Level 6 wells host hydraulic isolated junctions caused by cased main bore and a cemented or uncemented liner in the lateral. The procedures include drilling two separate wells under a certain depth which are then isolated from one another by a pre-constructed one-piece junction that can hold a dual-bore casing.

2.3 Definition of a fishbone well

A fishbone (or herringbone) well (Figure 6), consists of a main horizontal well with laterals, also referred to as branches, deriving from it (Al-Rbeawi & Artun, 2019). Its geometry is quite identical to that of a fish skeleton, where the ribs are connected to the backbone (Al-Rbeawi & Artun, 2019). This emerging drilling technology adequately competes with other methods of development and stimulation, such as drilling long horizontal wells and using hydraulic fracture (Al-Rbeawi & Artun, 2019). Particularly, the petroleum fields in which this type of wells predominate are those of high heterogeneity, laterally extended, and thin-layered. Unconventional resources are also another great example of high utilization of such wells.

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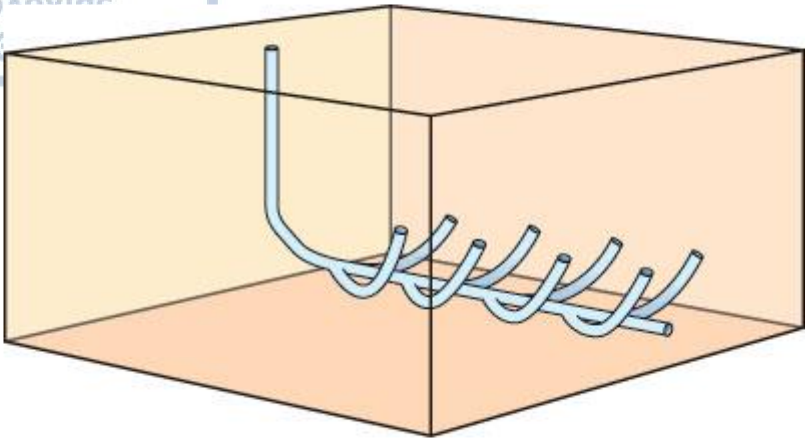

Figure 6: *Schematic representation of a fishbone well.*

(www.glossary.oilfield.slb.com/en/Terms/f/fishbone_wells.aspx)

2.4 The distinction between stimulation and field development methods

At this stage, it is essential for fishbone completion and fishbone stimulation to be distinguished from one another. Generally, when referring to fishbone completion, the act of drilling the main horizontal well with a Rotary Steerable System and each branch with a positive displacement motor is outlined (Bazitov et al., 2015).

On the contrary, fishbone stimulation is the method of drilling small diameter holes around a main horizontal well using multiple small diameter drill bits or needles, which are released simultaneously to penetrate the formation - a technique invented by the Norwegian company "Fishbones AS". It is aimed to be a fast and simple stimulation method for reservoirs of less than 25 meters of thickness (Bjørnseth et al., 2019), and to provide better control in terms of more evenly distributed tunnels with controlled penetration length than the more randomly spread cracks induced by hydraulic fracturing (Rice et al., 2014). The drill bits are typically used against clastic, non-reactive-to-acid formations through a procedure called Multilateral Drilling Stimulation Technology (MDST), while penetrating with needles is preferred against carbonate formations through a process called Multilateral Jetting Stimulation Technology (MJST) (Rice et al., 2015).

As can be concluded, fishbone completion and fishbone stimulation differ in the intervention extension scale. It is also understood that in large areas they can be used cooperatively. The first method may be applicable when designing a general development plan of a petroleum

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system, while the method of stimulation may be used individually at every well to solve local problems.

2.5 The advantages and difficulties associated with fishbone wells

The advantages of using fishbone wells can be grouped as follows:

- **Limitation of land use, time, and resources.**
  The use of a single vertical wellbore with several horizontal sidetracks reduces the surface land needed which can be very beneficial in sensitive, limited, or populated areas where accessing multiple drilling locations is challenging or impossible (Durst et al., 2012; Bone et al., 2016). There are cases where these petroleum fields are located beneath areas with severe climate conditions (e.g. within the Arctic climate zone) (Voronin et al., 2017), where placing and maintaining drilling infrastructures present serious difficulties. Building one drilling site also limits the cost and the overall time needed for the rig up and rig down procedures (Xing et al., 2012). Casing and cementing materials are significantly reduced, fewer drilling fluid volumes are required, and the cost of mud treatment and cuttings disposal is lowered (Xing et al., 2012). The cost of operating the field, such as producing and transporting hydrocarbons is also reduced (Xing et al., 2012) as its life cycle shortens (Enyioha & Ertekin, 2017).

- **Mitigation of the financial risk that accompanies the complex deposits.**
  The hydrocarbon market has reached a stage where exploitation of geologically complex fields is necessary to continue its growth (Voronin et al., 2019). When used in compartmentalized reservoirs, fishbone completion can enhance productivity and the overall hydrocarbon recovery (Voronin et al., 2017). They also present a worthy solution for extreme horizontal and/or vertical permeability anisotropy (Al-Rbeawi & Artun, 2019). In fact, their maximum potential is reached when used at heterogeneous reservoirs due to the bigger total effective well radius caused by sidetracks that diverge in three dimensions, increasing vertical and horizontal sweep (Voronin et al., 2017). The resulted connectivity of different layers mitigates the economic risk in such intensively layered reservoirs (Xing et al., 2012). As a result, the increased cost due to the acquisition of multiple geological and geophysical data at each stage of the project can be mitigated by the high efficiency of the well (Abaltusov et al., 2019).

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- **Efficient alternative to classical stimulation methods.**

  Fishbone shaped wells consists of an alternative stimulation method to hydraulic fracturing but without the disadvantages of increased cost and environmental impact (Al-Rbeawi & Artun, 2019; Hassan et al., 2017). Regarding the stimulation method, Fishbones AS refers to a 50% reduction in CO_2 emissions compared to hydraulic fracturing. It has also been demonstrated that their productivity is higher than that of both multi-fractured wellbores in relatively low permeable reservoirs (Hassan et al., 2017) and simple conventional long horizontal wells (Xing et al., 2012). They rise productivity by extending the pay zone (Voronin et al., 2017) caused by enlarging the bottomhole area that is in contact with the reservoir (Hassan et al., 2019). Particularly for the fishbone stimulation, this is achieved by surpassing the near-bore damaged zone, thereby reducing the skin factor (Rice et al., 2015) and drilling past any inner reservoir barriers, such as mudstones of marine flooding surfaces (Torvund et al., 2016). In addition, there are cases where hydraulic fracturing is not effective due to the plastic behavior of the rocks. In a very short time, the artificial fractures that were supported by the proppants, close, shrinking the production (Lux et al., 2016). Even if the geological formations are ideal, there is a level of unpredictability of fracture propagation due to inadequate knowledge of formation stresses (Xiance et al., 2009).

- **Increased control of the drainage area.**

  It is possible to accurately select the installation area of each lateral away from undesirable reservoir parts such as the gas cap (Akhmetov et al., 2019). Moreover, the bigger drainage area due to multiple branches affects the type of flow and the shape of the fluid layers nearby the wellbore. As a result, a delay of gas and/or water breakthrough is observed while maintaining a high productivity index (Rylance et al., 2020). However, if early gas and/or water production occur, the use of smart bottomhole completion can further adjust the sweeping area (Alyan & al Sowaidi, 2019) by isolating certain branches.

However, there are some difficulties that need to be addressed when deciding on the use of this type of well. The most noticeable are the following:

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- According to the literature, the most important challenge associated with fishbone wells is their proper optimization regarding the number, the length, the angle, and the distance between the laterals (Xing et al., 2012).
- Due to the complexity of these wells, any attempt to simulate production can involve significant errors as many parameters have to be taken into account. To overcome this barrier, many studies have focused on the utilization of artificial intelligence to derive a general productivity index equation consisting of weighted factors to predict the performance those wells, ultimately highlighting them as a viable option for the industry (Hassan et al., 2019). In the case of fishbone stimulation, due to the narrow and short laterals, models of high resolution around the wellbore should be created.
- Last but certainly not least, except for the fishbone stimulation method which follows a standard procedure in a pre-drilled horizontal well, the initial drilling of a main horizontal borehole with longer and wider branches by using state-of-the-art tools such as rotary steerable systems, always carries the risk of not being able to sufficiently penetrate the oil target, along with all the other problems that may arise and are related to the complex geometry of the entire structure.

3. Methods and tools used in the drilling of fishbone wells

3.1 Stimulation methods

3.1.1 Multilateral jetting stimulation technology

The stimulation method of multilateral jetting is performed by a set of four high-strength tubes called needles which are hosted inside a series of pipes, widely known as subs (Figure 7). The subs are placed in predefined intervals that match the areas of interest (Nofal et al., 2016) as part of the uncemented permanent liner completion (Freyer et al., 2009), and each one contains two production valves to assist the flow (Nofal et al., 2016) spaced 180 degrees from each other (Rice et al., 2014). Each needle is attached to a sealing nipple which are crafted on the sub at an angle with the liner's axis (Freyer et al., 2009). The needles are made of titanium, and their diameter is 0.8 cm. They exit the liner at an angle of nearly 40 degrees, and as they propagate, the initial bending causes them to reach a final angle of 90 degrees (Rice et al., 2014). Angle build-up rate of 4 to 11 degrees per meter is considered successful,

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Figure 7: A multilateral jetting stimulation technology sub consisting of four needles. (Bjørnseth et al., 2019)

whereas anything higher can cause excessive friction and terminate the drilling for the individual needle (Bjørnseth et al., 2019). When fully deployed, they can reach a length of 12 meters (40 feet). In the front end of each needle, there is a jetting nozzle that allows circulation of fluid (Bjørnseth et al., 2019). Two models of subs are available, one with 5.7 inches outer diameter and another one with 7.9, supporting main horizontal boreholes from 6 to 9.9 inches wide.

Deviation from the original system configuration is possible. An example of such a case is the needles used at the Valhall field. They consisted of an outer aluminum layer which was dissolved by pumping 10% hydrochloric acid right after the drilling procedure, leaving the inner slotted titanium tube exposed to the formation. This design allowed for flow both in the annulus and inside the needle, but with the drawback of using the less reactive water for the jetting operation. The subs were also modified to host four one-way production valves instead of two (Bjørnseth et al., 2019).

The whole process is as simple as running conventional drill pipes into a well with no special preparation needed on deck. In the beginning of the assembly process, and the subs gradually descend into the well as part of the lower completion. They are designed so that swellable packers can be placed in between them, allowing for zonal isolation. When everything reaches the desired depth, the liner's position is secured by setting the liner hanger anchors which also causes isolation of the liner's annulus. The needles are activated by reverse flow of acid, usually 15% hydrochloric acid (HCl), in a process where fluids are pumped

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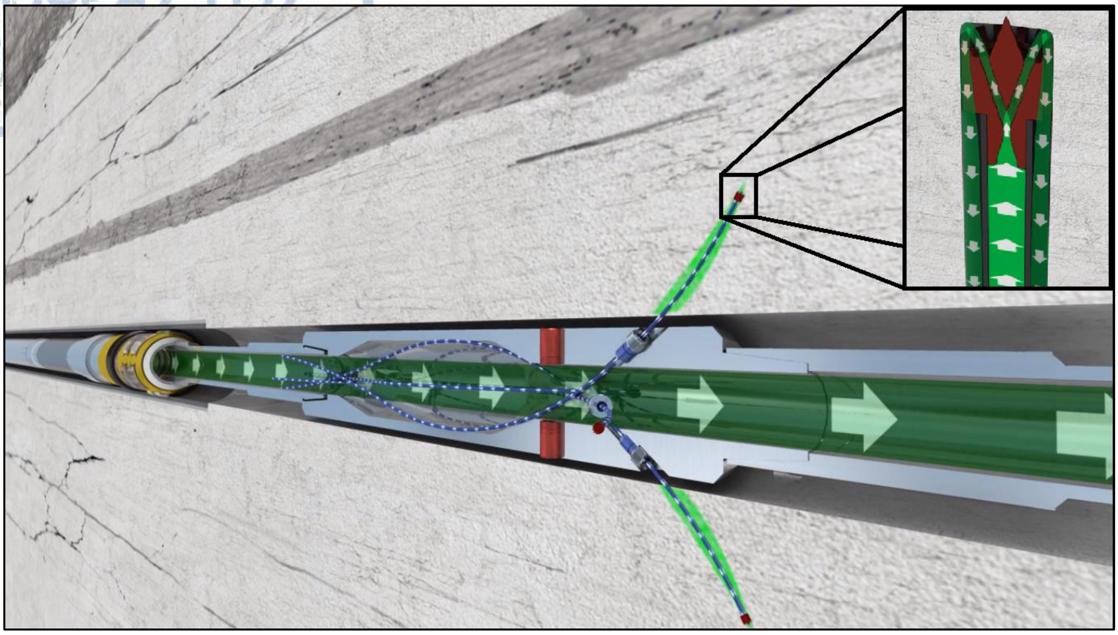

***Figure 8:** Schematic illustration of the jetting process during the extension of the drilling needles regarding the method of multilateral jetting stimulation technology. The arrows indicate the direction in which the hydrochloric acid is moving as It is forcibly pumped into the liner. As it exits the needles, it corrodes the carbonate rock, and due to the pressure exerted on the needles, they penetrate deeper into the rock. (Fishbones AS)*

forcibly into the production well from the rig's standard pumps at a pressure of around 3000 psi (Rice et al., 2014). The differential pressure between the inner part of the subs and the formation, releases the needles from the seal mechanism and causes them to extend simultaneously towards the surrounding rock in a curved trajectory while fluid is being jetted out from the nozzles (Figure 8) (Bjørnseth et al., 2019). Penetration is achieved by both mechanically eroding and chemically dissolving the reactive rock ahead of the needles, leading to laterals with a diameter between 1.2 and 1.9 cm (1/2 – ¾ inches) (Rice et al., 2014). Rock dissolution eliminates the need for fluid circulation to the surface because no cuttings are present, making the method ideal against carbonate formations. Open hole pressure-activated anchors keep the liner in place (Torvund et al., 2016). Acid loss through the sub's production valves is prevented by a pair of balls that move into place, blocking the passage when positive pressure is applied inside the liner (Torvund et al., 2016). During the production phase, the balls are displaced away from the holes allowing hydrocarbons to flow into the well.

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Figure 9: *Needle deployment verification test regarding the method of multilateral jetting stimulation technology. Foamed cement blocks were used as substitute for the reactive rock. (Bjørnseth et al., 2019)*

According to Rice et al., 2014, an auxiliary factor in determining the termination of the process is an identification mechanism carried by the needles, which stops the acid from being jetted to the rock when the maximum extension is reached. As a result, the pressure inside the wellbore rises, which notifies the personnel that the drilling procedure has finished. Laboratory experiments such as that shown in Figure 9, have demonstrated a rate of penetration equal to 32 meters per hour which can be reduced to approximately 20 minutes for full extension of the needles. The time needed for the trial installation at the Valhall field of the North Sea is in line with the experimental result (Bjørnseth et al., 2019).

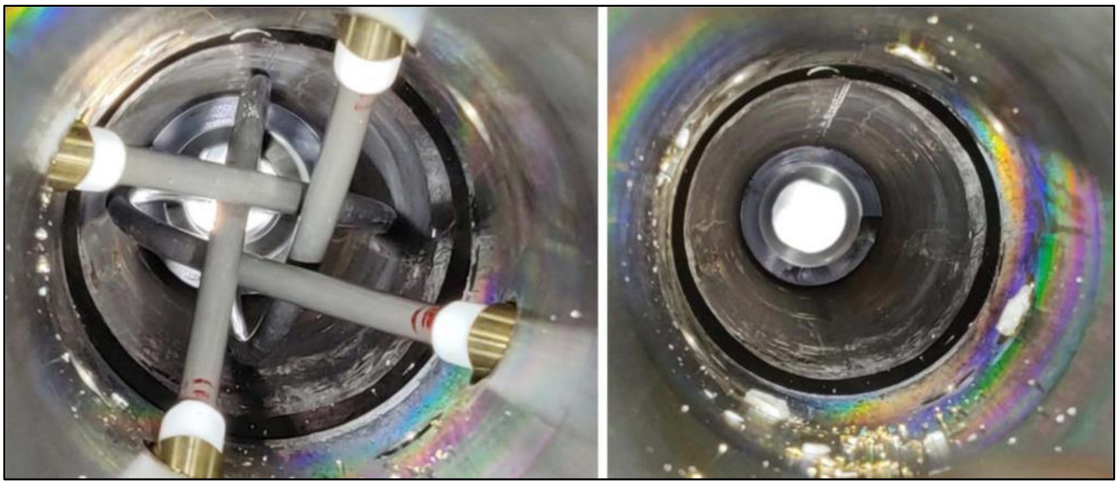

Figure 10: *Multilateral jetting stimulation technology sub hosting four needles.*

Left: Before the cutting tool. Right: After the "fishbasket" cutting tool is run inside the liner. (Bjørnseth et al., 2019)

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When the propagation is completed, each lateral hole is supported by the needle, which is left in place (Freyer et al., 2009). It is then possible for a coiled tubing cutting tool called "fishbasket" to be run inside the liner and cut all the sections of the metal tubes that did not extend beyond the sealing nipples, leaving space for hydrocarbons to flow (Figure 10) (Nofal et al., 2016). The needle pieces are retrieved on the surface, and by measuring their total length, conclusions can be drawn as to the total length of penetration of the remaining sections, and thereby, as to how successful the procedure was (Bjørnseth et al., 2019).

As presented in Figure 11, production fluids flow through each needle annuli and arrive at the annulus of the main horizontal hole, where they enter the liner through the production valves (Rice et al., 2015). Except for the branches, the main horizontal open hole section also contributes to the production, as hydrocarbons can enter the annulus from the entire length of the liner and eventually reach the production valves, beginning their journey to the surface.

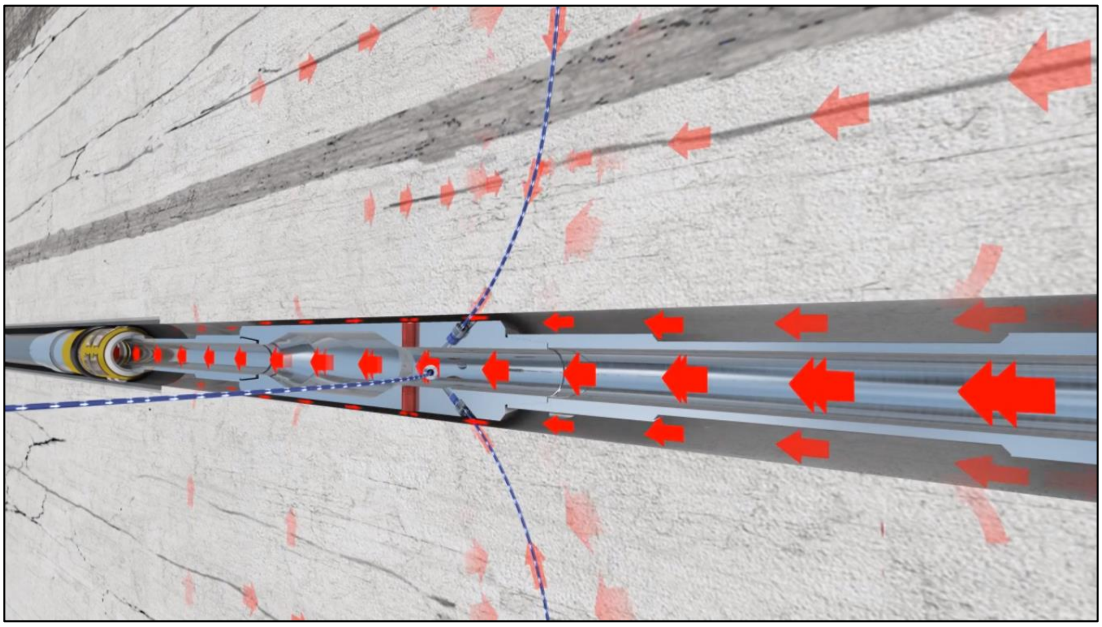

Figure 11: *Schematic representation of the production regarding the method of multilateral jetting stimulation technology. The arrows show the path that the fluids follow as they flow from the rock into the liner. The first possible route is through the annuli of the needles to reach anulus of the liner and from there, through the production valves, to finally enter the liner. The second case is the initial entry of fluids inside the needles and their flow directly into the liner. The last case is their initial inflow into the anulus of the main horizontal well and then their movement inside the liner through the production valves. (Fishbones AS)*

Numerous tests had been conducted since 2008 when the system was still in the research and development phase until the November of 2013 when two subs were deployed for the first

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time in a Coal Bed Methane production well with encouraging results (Rice et al., 2014). The first pilot application of this system took place in April of 2014 in the Austin Chalk carbonate formation in Texas, which is a tight limestone reservoir with 5% porosity and 0.5 mD permeability, (Rice et al., 2014) and resulted in 8.3 times higher production in the first month. The system consisted of 60 laterals hosted inside 15 subs and drilled in less than 5 hours. The liner was kept in place by three open hole anchors (Rice et al., 2014). Since then, it has been tested in more than 20 wells worldwide, mainly in naturally fractured carbonate formations of the Middle East. According to information obtained from the website of Fishbones AS, a total of 2804 needles have been installed in 30 different locations worldwide with the deepest point being at a true vertical depth of 5495 meters. The average increase in production is documented to be an extra 100%. The range of utilization is not limited to oil and gas production but also extends to water injection (Bjørnseth et al., 2019).

3.1.2 Multilateral drilling stimulation technology

The fishbone drilling stimulation technique includes three small diameter high-durability needles, which are hosted inside a sub called “Dreamliner” (Figure 12). The initial part of every needle is connected to a dedicated turbine, while their front section hosts a small drill bit. The penetration of each needle can reach up to 10.8 meters (35 feet), the array of subs is integrated into the production liner, and every sub has two production valves.

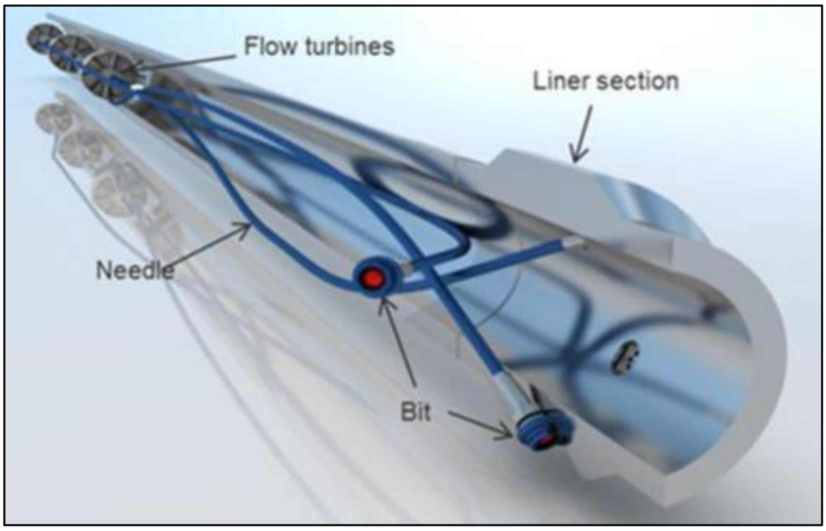

Figure 12: *The internal structure of a multilateral drilling stimulation technology sub that houses α small-diameter drill bit at the end of each of the three needles. Small turbines inside the liner are connected to the needles and their rotation during the circulation of a high-pressure fluid provides the necessary torque to the bits. (Rice et al., 2015)*

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Dreamliner's joints are designed so that open hole anchor can be accommodated in between them. The flow of high-pressure fluid inside the liner sets the anchors in place, burst the disk at the liner's shoe, and pushes the needles into the formation. It is also used by the turbines to rotate and lubricate each needle's drill bit (Torvund et al., 2016). The targeted reservoir is usually a consolidated formation such as sandstone. The drilling phase is analogous to the one mentioned in the jetting method but in this case, there is fluid circulation to the surface. The process begins by reaching a flow rate between 1000 and 1600 litres per minute (6 – 10 bbl/min), which brings the turbines to the appropriate RPM for drilling to start. The cuttings from the small drill bits are circulated to the surface (Figure 13) (Rice et al., 2015) through the various annuli. The turbines are located before the drill bits, and the flow can push them towards the small openings while the needles penetrate the surrounding formation. Because the fluid is spread across the needles and the liner, both the flow rate and the differential pressure is higher at the beginning of the liner (heel) than at the end of it (toe) (Rice et al., 2015). Consequently, the number of needles that can be installed across a liner depends on the total capacity of the pump array (Freyer et al., 2009).

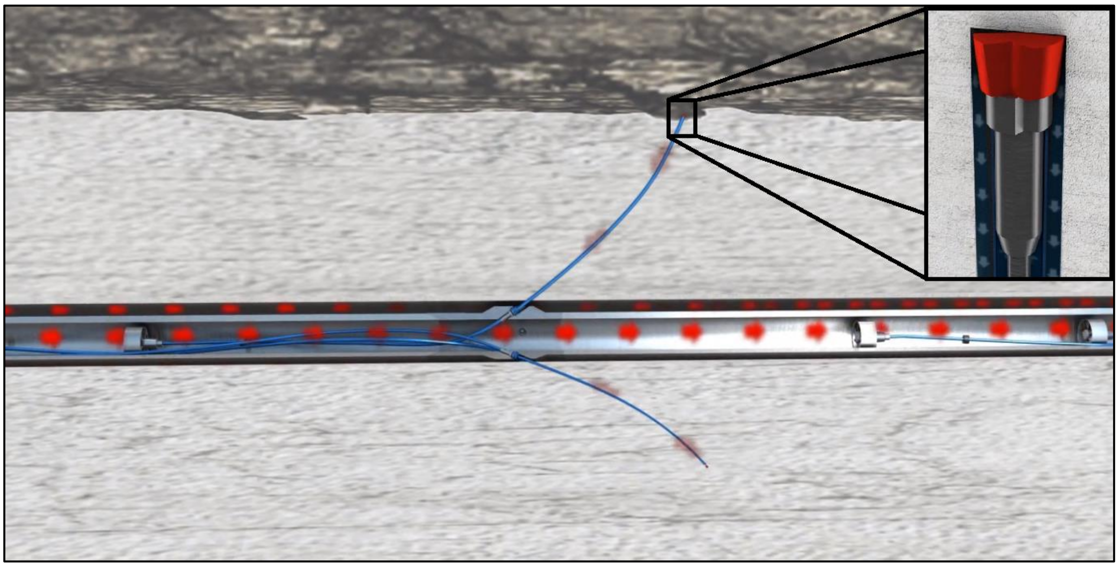

Figure 13: *Representation of the drilling phase regarding the method of multilateral drilling stimulation technology. The arrows indicate the flow of drilling mud, through which the cuttings powder is circulated to the surface. (Fishbones AS)*

Within few hours, when pressure measurements indicate that the needles are fully extended, the liner hanger is set, sealing the annulus of the main horizontal well. Afterwards, the liner hanger setting tool is removed, and the upper completion is run. Production occurs similarly

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to the jetting method. Short exposure of turbines to production fluids results in their dissolution (Rice et al., 2015).

3.2 Large-scale fishbone drilling

3.2.1 Overview of the drilling procedures

Fishbone wells may be drilled by following one of the two drilling sequences: backward drilling and forward drilling (Yu et al., 2020). Backwards drilling is the process in which the main horizontal well is drilled first from heel to toe, followed by the construction of each branch. The elevation of the main horizontal wellbore at the kick-off points is usually greater than that of the laterals, and, to further facilitate the completion processes, every branch slops downwards at the beginning of each corresponding kick-off point (Yu et al., 2020). When re-entry to the main horizontal well begins, the bottom hole assembly is located inside the branched hole (Yu et al., 2020). In the forward way, drilling part of the main horizontal well is alternated with drilling a sidetrack (Yu et al., 2020). This indicates that every following branch is a sidetrack of the previous one and the main hole is drilled last (Figure 14) (Abaltusov et al., 2019). In both ways the branches can have the same diameter as the main horizontal section (Abaltusov et al., 2019). However, it is not uncommon to drill smaller diameter branches so that to avoid the entrance of the liner into them (Bazitov et al., 2015). There are also cases where very few logging-while-drilling tools could fit inside smaller diameter branches (Bazitov et al., 2015), limiting the available real-time information. Main hole of similar diameter as that of the branches can lead to the completion of a project at an earlier date because of the reduction of the tripping time that is required to replace the drill bits (Bazitov et al., 2015). The design of backwards drilling only allows for double open hole completion whilst pipe completion for the main well is possible at the forward type (Yu et al., 2020). It has been pointed out that increasing the branch hole build-up rate increases the chance of bottom hole assembly re-entering the main hole at the forward drilling (Yu et al., 2020). Xing et al., 2012, pointed out that a crucial step for successful sidetracking is the quick separation of the lateral from the main horizontal section. The success rate is also improved as the distance from the top of the bit to the bending point of the motor decreases (Yu et al., 2020). Smaller angle of housing and smaller body stabilizer can also be beneficial for the re-entering procedure (Yu et al., 2020).

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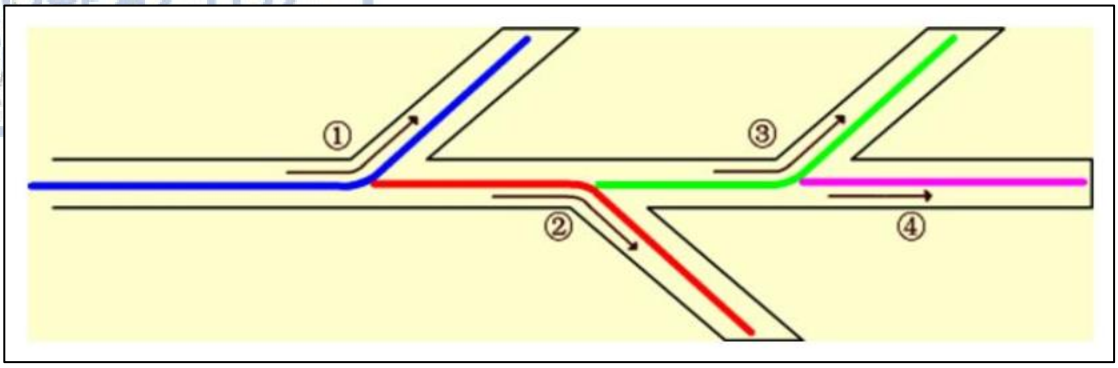

Figure 14: *Schematic representation of the forward drilling method where every new lateral is a sidetrack of the previous one. Part of the main wellbore and the first lateral are drilled first (1), followed by a kick-off operation to drill the next part of the main hole along with the second lateral (2). The same process gets repeated for the third lateral (3) and finally the last part of the main well is drilled (4), which is a sidetrack from the last lateral. (Yu et al., 2012)*

3.2.2 Geosteering

When planning a new directional well, one important decision that needs to be made is to select the most appropriate bottom hole assembly with a steering mechanism. It is a decision that will not only affect the total drilling cost (Al Dabyah et al., 2016) but will also determine the success of the project. Parameters such as the rate of penetration, the well trajectory and the doglegs should be carefully examined to allow easy placement of the completion parts in the well and to ensure maximum production (Alrushud et al., 2018).

Exiting the horizontal mother bore at the kick-off point and beginning the drilling of a lateral is a very important series of steps. Successful sidetracking in an open hole without the use of a whipstock, is highly dependent on the geology and especially on the rock density of the corresponding interval where kickoff point is planned to take place (Abaltusov et al., 2019). Well logging and optimal geosteering methods can make the difference. Usage of Rotary Steerable Systems (RSS) is ideal for horizontal sections that are designed to have great length inside reservoirs that are in shallow depths (Abaltusov et al., 2019) and have small thickness (Bazitov et al., 2015). Their adoption has become economically viable due to the higher production rate of the horizontal wells that these drilling devices are mainly used for. In many cases, the prime challenge that these systems face is successfully drilling the branches inside a narrow interval that matches the reservoir’s thickness (Bazitov et al., 2015). Collaboration between drilling engineers and geologists is necessary for a successful outcome. Specifically for the engineering team, directional drilling and measure-while-drilling engineers attend the

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rig and are responsible for performing the drilling and monitoring the real-time survey tools, while the rest of the team, which consist of drilling engineers and directional drilling technical support engineers, contribute remotely from the service company's offices by planning and monitoring the procedures and consulting the rig team (Teregulov et al., 2018).

Re-entering a specific sidetrack at a kick-off point is also of critical importance in both drilling and completion procedures of fishbone wells (Yu et al., 2020). As the completion level becomes higher based on the TAML ranking, certain devices are being used that provide a solution to this problem. However, their complexity that goes along with the risk as well their cost prevents their application in real projects (Yu et al., 2020). In fact, most of fishbone wells are completed with low level architecture where a screened liner may be used at the main horizontal well while the branches are left completely opened. This choice is mostly favorable for the consequent larger drainage area and the reduced cost. The predetermined completion method indicates the shape and the drilling sequence of each lateral (Yu et al., 2020).

There are generally two categories of drilling systems that are being used in directional drilling: Steerable motors and Rotary steerable systems.

3.2.3 Steerable motors

Steerable motors, also known as positive-displacement motors, are mud motors that either incorporate a bending mechanism near the bit (bent-housing mud motors) or they are fitted with a bent sub near the bit. They were introduced in the late 1960s, and since then, they have found a place in a wide range of applications, from kicking-off to drilling a whole section of a directional well.

Their operating method is based on the Moineau principle. Drilling the kick-off section requires a motor with a pre-arranged deflection at the bending mechanism. When the bit is in place, drilling fluid is pumped inside the drill string by a positive displacement pump that injects the same amount of fluid per revolution. The hydraulic horsepower of the fluid is used by a system of rotor and stator, similar to those shown in Figure 15, to drive the bit. The method is an inverted process of the way that a progressive cavity pump works, where fluids enter the space between the rotor and the stator and travel upwards due to the combination

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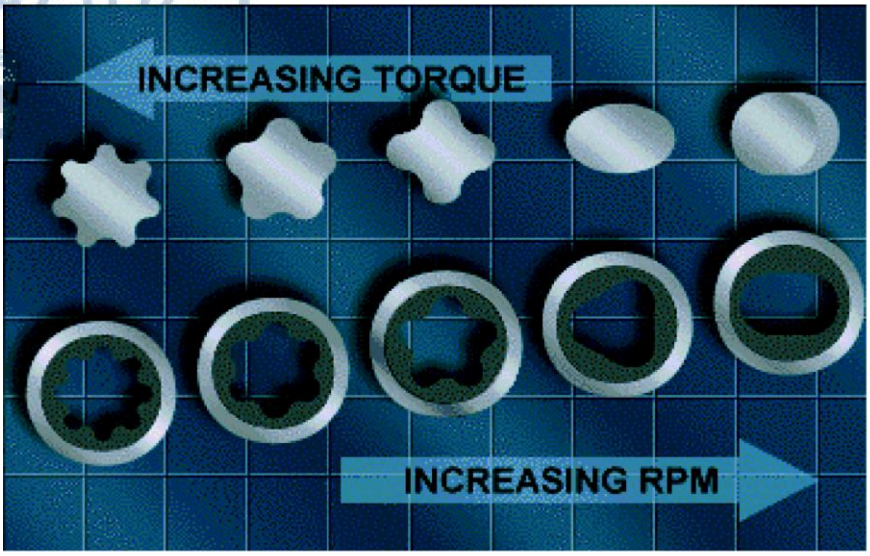

Figure 15: *Various configurations of a rotor – stator system. The number of lobes determines the torque of the system and the rotational speed of the rotor. (https://petrowiki.spe.org/Directional_deviation_tools)*

of rotor-stator geometry and rotation. The rotation is caused by the transformation of electrical power into mechanical. In the case of mud motor, the hydraulic horsepower of the injected fluid is what causes the rotor and consequently the drill bit to rotate, while there is no rotation of the drill string. This method is widely known as "sliding" because the drill string does not rotate but rather slides inside the hole as the latter is gaining length. It is the mostly used procedure when building up or correcting the angle of a lateral.

After drilling the first section of a lateral at the desired angle, straight drilling of the remaining interval is achieved by rotating the entire drill string. At this point, straightening of the bending sub is impossible, and as a result, drilling over-gauged holes as shown in Figure 16 is inevitable, which, combined with the alternation of getting ahead and falling back to the predefined well path, compromises completion operations (Al Dabyah et al., 2016).

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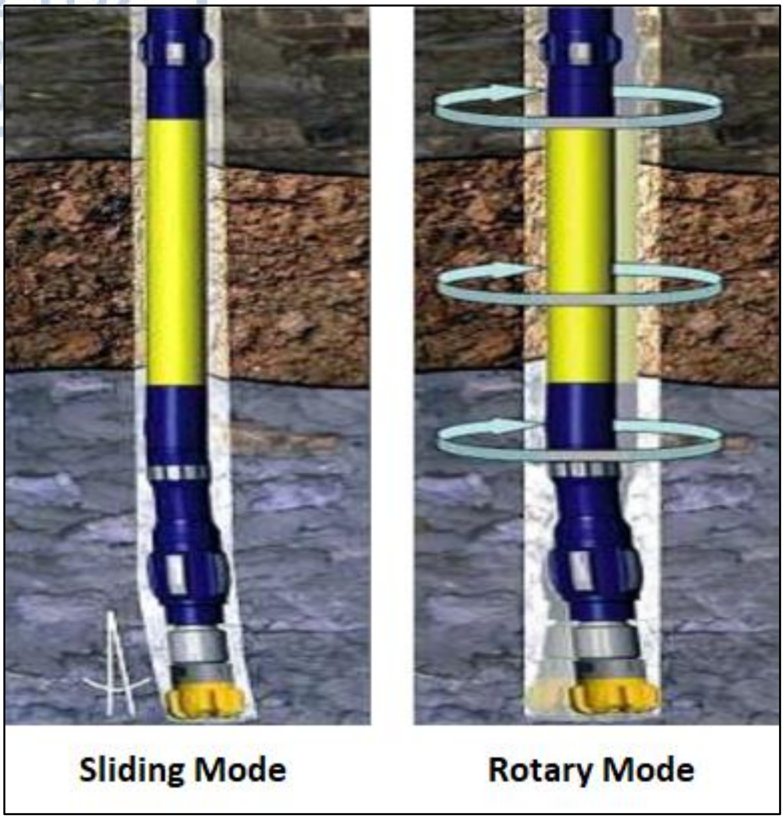

Figure 16: *Representation of a mud motor assembly in sliding and rotary modes. During the rotary operation where the entire drill string rotates, an interval of larger diameter than normal is drilled. (Al Dabyah et al., 2016)*

3.2.4 Rotary steerable systems

A rotary steerable system (RSS) is an array of tools designed for real-time directional drilling with continuous rotation throughout the drill string. They were introduced to the industry in the 1990s, completely changing the way directional drilling was performed, and their continuous improvements have significantly increased the confidence in them (Sugiura, 2008). They provide on-the-fly geosteering capability to ensure entrance to a predetermined reservoir target zone, which is usually not located exactly underneath the rig site but further away. Their better performance at delivering increased directional control and reduced deviation from the predefined wellbore profile have been key factors in their broad adoption, as they have set them apart from the less cost-efficient steerable motors. The extensive and understandable measurements of RSS' logging-while-drilling tools allow geoscientists to take important decisions during the drilling process that can significantly affect the outcome of a project (Al Dabyah et al., 2016). Based on the steering mechanism, the rotary steerable

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systems are categorized into two types: point-the-bit and push-the-bit (Barton et al., 2013). Both categories utilize various combinations of forces to guide the bit (Figure 17). There are also machines which derive from a combination of the previous two, resulting in various drilling methods such as the continuous proportional steering method (Alrushud et al., 2018). The most common types of directional wells usually drilled by an RSS are the following:

1. Horizontal wells, which are long wells with an inclination usually greater than 85°.
2. Multilateral wells, which, as mentioned above, is a system consisting of a main borehole with at least one secondary well deriving from it.
3. Extended-reach wells, whose measured depth to true vertical depth ratio is at least 2:1. They are used to target nearby reservoirs but without the process of building any additional dedicated infrastructure above them. A representative example of their utilization is the development of near-shore petroleum systems from the onshore.

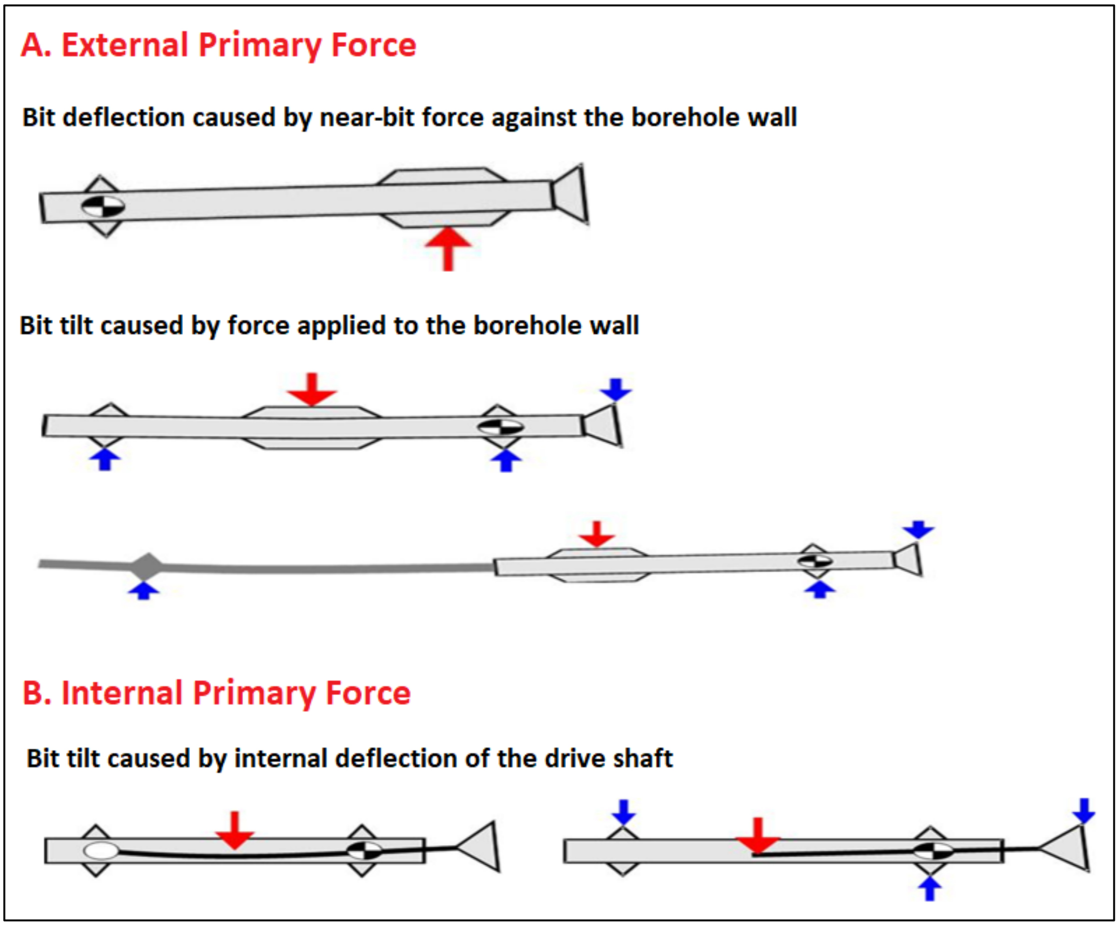

Figure 17: *Categorization of rotary steerable systems based on the position of the primary force causing the bit deflection. This initial force is symbolized by the red arrows, while the blue ones represent the secondary forces that develop. The circles are the fulcrum points, on either side of which the direction of movement is reversed. (Al Dabyah et al., 2016)*

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3.2.4.1 Point-the-bit rotary steerable systems

The first category includes systems that incorporate a mechanism that is responsible for guiding the bit in the desired direction by applying the appropriate vertical pressures to the steering shaft. Although there are small variations between the tools produced by each company operating in this sector, the main components that make up a point-the-bit RSS remain the same (Voronin et al., 2017).

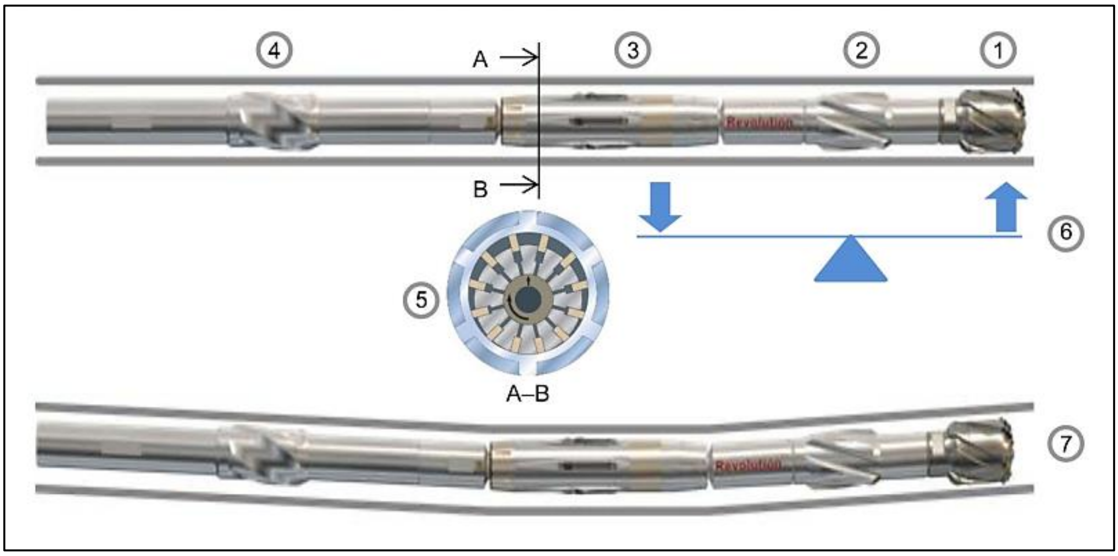

Figure 18: *Representation of a point-the-bit rotary steerable system assembly composed of: 1) the drill bit, 2) a near-bit pivot stabilizer, 3) the bias unit, and 4) a module with an inclinometer and a stabilizer. The internal structure of the bias unit is shown in section A-B (5), which illustrates the pistons through which the steering shaft is deflected. The pivot stabilizer between the bias unit and the drill bit acts as a fulcrum point (6). In this example, the steering shaft is deflected downwards which translates into an upward movement of the drill bit (7). (Voronin et al., 2017)*

As illustrated in Figure 18, at the lower end of the assembly is the drill bit (1), followed by a near-bit pivot stabilizer (2). Next in line is the non-rotating bias unit (3), in which the deviation of the steering shaft takes place, and finally, the RSS controller and inclinometer module, along with a stabilizer (4), complete the toolkit (Voronin et al., 2017).

Inside the non-rotating bias unit, there is a hydraulic system consisting of 12 groups of pistons, positioned 30 degrees apart from each other, around the axis that transmits the rotary motion to the drill bit. When activated, they deflect the steering shaft in the opposite direction and with the correct amount of tilt (5). The near-bit pivot stabilizer acts as a fulcrum point enabling bit deflection in the opposite direction of the steering shaft’s deflection but with the same

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intensity (6). In the example of the figure, as the upper pistons are activated, they push the steering shaft downwards which in turn, due to the stabilizer, directs the drill upwards (7) (Voronin et al., 2017).

Three anti-rotating levers located outside and around the bias unit maintain contact with the borehole walls, preventing the unit from following the rotational motion to which the rest of the drill string is subject. This allows the RSS to be constantly aware of its position in space in order to use it as a reference to guide the drill bit in the right direction (Voronin et al., 2017).

However, keeping the bias unit completely stable throughout the workflow is practically impossible. Small-scale rotations can be counteracted by re-synchronizing the hydraulic forces to keep pace with the new position of the pistons, maintaining the predefined drilling profile. Nevertheless, when the rotation time of the bias unit exceeds 6% of the total drilling time, not only is there no proper guidance to the predetermined oil targets, but if the problem is not addressed immediately, a vicious cycle is likely to ensue, widening the consequences. Suppose that an extensive rotation of the bias unit begins while the drill bit is not in its natural position. In this case, the bit not only spins on its axis, but also rotates around the axis of the bias unit. This leads to the drilling of an over-gauged hole, as is the case with a mud motor in rotary mode. But the problem does not end there. As drilling progresses, the bias unit will inevitably find itself in this larger diameter interval. Therefore, it will continue to rotate, since the anti-rotating levers that should ideally keep it stable will not be in close contact with the walls (Voronin et al., 2017). This self-sustaining cycle will carry on until the hole diameter returns within the operating limits of the RSS, which can be achieved by zeroing the bit deflection and proceeding by drilling a length at least equal to the distance of the front of the drill bit from the farthest edge of the bias unit.

3.2.4.2 Push-the-bit rotary steerable systems

The philosophy behind the operation of a push-the-bit RSS is to generate a side force towards one direction to guide the bit to drill towards the opposite direction. The force is generated by a set of pads that are mounted on the body of the RSS (Figure 19) at a small distance away from the drill bit. There are usually three pads present and, when activated, they extend towards the wellbore wall. As the drill string rotates and given the fact that the pads are placed on a rotating unit after the last fulcrum point, which is usually a near-bit stabilizer, each pad is activated once per revolution and only when it reaches the opposite side of the desired well

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path direction while the rest return to the neutral position. If the unit is stationary, the desired pads maintain extended throughout a maneuver (Sugiura, 2008). During their interaction with the wall, they push the lower part of the drill string to the opposite side. Consequently, the drill bit is constantly headed towards the planned well path. The activation is achieved by a control valve which is traversed by a portion of the circulated mud. The valve is oriented into the desired direction, and each pad that crosses it accepts the force of the flowing mud, therefore extending (Alrushud et al., 2018). As shown in the figure above, there are many configurations of pads and fulcrum points and, by alternating the direction of the primary external force accordingly, the same result can be achieved.

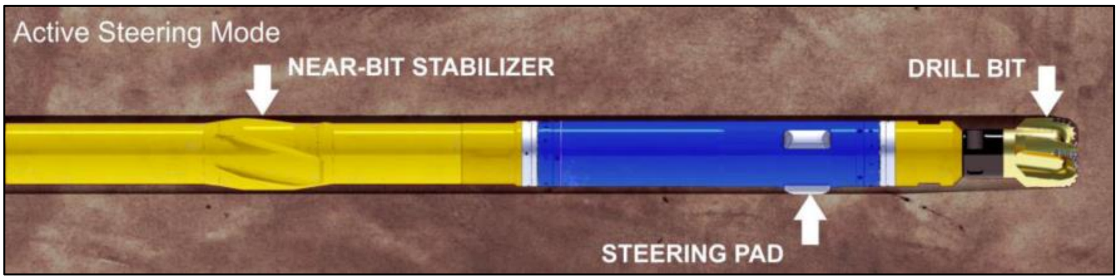

Figure 19: *Part of a push-the-bit rotary steerable system assembly. (Hakam et al., 2014)*

3.2.5 Sidetracking sequence

The process of drilling a lateral requires the fulfilment of two prerequisites at the kick-off point: the building of a tangent section, which is immediately followed by a "ramp-up" interval. The position of every kick-off point should be carefully selected based on measurements from the instruments in the bottom-hole assembly to ensure that the entire process is carried out in a uniform formation. In the case of dense rocks, sidetracking duration may triple or even quadruple (Voronin et al., 2017).

The first few meters after a kick-off point are considered as the "tangent section". Its length should be slightly longer than the length of the bottom-hole assembly, although successful sidetracking operations have been accomplished in the past without fully meeting this criterion (Voronin et al., 2017).

The procedure begins with the ledge building phase, which has an indicative duration of approximately one hour. The RSS is pointed downwards with the maximum deflection and the drill string begins to rotate without gaining depth (Figure 20: 2). Hence, enlargement of the main wellbore occurs until the initial separation of the new lateral becomes clear. If a point-

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the-bit RSS is used, the anti-rotation levers must be in close contact with the walls to keep the bias unit stable (Figure 20: 1), therefore, the diameter of the main wellbore at this section must be suitable for the size of the specific bias unit. During the final step of this phase, as the entire bit slowly enters the new lateral, the deflection must be gradually reduced until the bit is aligned with the axis of the drill string, delivering smooth separation and a tangent section of minimal tortuosity (Voronin et al., 2017).

Figure 20: *Representation of the sidetracking sequence at the kick-off point performed by a point-the-bit rotary steerable system. The procedure begins with the ledge building phase. The bias unit is in close contact with the walls of the main horizontal well (1) and the drill bit is pointed downwards with the maximum possible deflection (2). (Voronin et al., 2017)*

The next phase is called "time drilling" and involves a deeper opening of the tangential portion. After a few meters of drilling, the bias unit will inevitably enter the enlarged area and as it loses contact with the walls, it will begin to rotate (Figure 21: 1). By the time this happens, the deflection should have returned to zero (Figure 21: 2), so from there on, only linear drilling will be performed. Time drilling ends when contact is made between the anti-rotation levers and the wall of the new lateral (Figure 22: 1). This contact is a special condition for the continuation of the drilling of the lateral, since otherwise, it will not be possible to turn the bit to further separate the two boreholes. Thus, the tangent section must have the appropriate minimum length to fit a large part of the bottom-hole assembly and at least up to the bias unit. In addition, the absence of cavities in this part is certainly a decisive factor (Voronin et al., 2017).

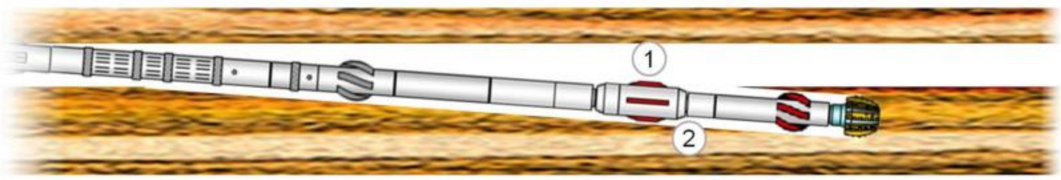

Figure 21: *The "time drilling" phase of the sidetracking sequence, the objective of which is to build a tangent section that is long enough to host the bottom hole assembly. The process begins with the ledge building phase. The interval of an enlarged hole in which the bias unit must operate makes any guidance of the bit impossible (1). Thus, the tangent section is drilled with the bit in the neutral position (2). (Voronin et al., 2017)*

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A “ramp-up” section follows, where the bit initially tilts down (Figure 22: 2) once again and for a few meters to further maximize the angle between the two boreholes and, from there on, the drilling of the lateral to the right or to the left of the main borehole begins (Voronin et al., 2017). A similar methodology is followed when using different configurations of bottom-hole assembly and drill bit types, but each time it is adapted to the capabilities and limitations of the tools.

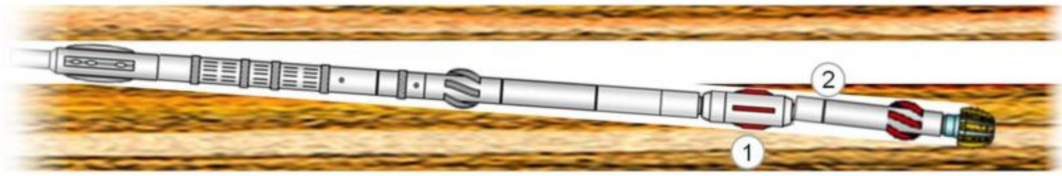

Figure 22: *The “ramp-up” phase of the sidetracking sequence, the objective of which is to further separate the two boreholes. Since the bottom hole assembly is inside the tangent section, the bias unit has regained contact with the walls so the drillers can re-direct the drill bit (1). From then on, adjustments are made to the bit’s inclination and azimuth to continue drilling the lateral in the desired direction (2). (Voronin et al., 2017)*

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4. Productivity of fishbone wells

4.1 The inflow performance relationship as an indicator of optimal layout

An Inflow Performance Relationship (IPR) curve is the geometric location of the points which express the different values of production rate, i.e., the volume of fluids that will migrate from the reservoir to the well, for the different bottomhole flowing pressure values that exist inside the well in the area adjacent to the reservoir. It is an indispensable indicator of reservoir performance that makes possible any kind of planning and forecasting. The correct interpretation of the curve can inform about the expected production in the long run, the condition of the reservoir around a well, and the necessary actions that may need to be taken to optimize the production (Ahmed et al., 2016).

On the other hand, a Vertical Lift Performance (VLP) curve, also known as an Outflow Performance Relationship (OPR), is a correlation between the flow rate at the surface and the bottom hole pressure. The output is affected by the well characteristics and equipment.

To compute the production at the surface, nodal analysis must be performed, considering both curves. Initially the IPR informs about the volume of hydrocarbons that will reach the well and at what pressure they will be. Then, through the VLP, the necessary equipment is determined taking into account the pressure drop that it will cause, so that the desired volume of fluids reaches the separator at the surface.

Because fishbone wells form a complex as they drain the same reservoir and eventually join into a central horizontal well, the concept of the IPR is used to describe any pressure drop that occurs up to the point where the main horizontal well becomes vertical, and the volume of hydrocarbons reaching that point.

To investigate the optimal layout of wells, the scientific community uses either dimensionless IPR, daily production, or cumulative production. A dimensionless IPR is the graph resulting from division of the bottom hole pressure with the average reservoir pressure and the flow rate with the absolute open flow rate. If the graphs are identical then the variable in question does not affect the flow. When one is larger than the other, then the factor under consideration has a positive effect on production. The reverse is true when one curve points to lower values than the other.

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4.2 Flow regimes

During the production phase of an intact reservoir, three distinct flow regimes are observed.

- The first in the sequence is always the transient flow. During this period, the disturbance in pressure caused by the well, which could be thought of as a wave that starts from it and propagates to every direction, has not reached the infinite-acting reservoir boundaries. As a result, pressure throughout the reservoir is a function of both location and time, and well performance is independent of the reservoir size. In the beginning, the pressure in the affected region and inside the wellbore continuously decreases and then stabilizes. Hydrocarbons flow linearly into the fishbone structure, and each lateral has its own drainage area where the pressure is not affected by the existence of the adjacent laterals (Yang et al., 2019). Transient flow may represent a short period at the beginning of the production phase of a high permeability reservoir but, as the permeability decreases, the pressure wave takes more time to reach the boundaries so transient flow may last for a longer period. Data collected during this phase can provide insights about various reservoir properties such as the permeability, the initial reservoir pressure, and the damage nearby the wellbore.
- Pseudo- (or semi-) steady state or Boundary Dominated Flow is the phase that follows the transient flow. During this period, the reservoir has produced for long enough so that the pressure wave has reached the boundaries. After that moment, in the case of pseudo-steady-state, the pressure at each point of the reservoir drops with the same constant rate over time, which results in constant flow due to the non-changing differential pressure. In the case of boundary dominated flow, the declining pressure at the reservoir boundaries is what controls the flow. Assuming a constant bottom hole pressure, the differential pressure, and therefore the flow rate, are continuously reduced. It is also during this period when volumetric analysis can be performed to estimate hydrocarbons in place. As for a fishbone well, during this period the lateral interaction begins forming a common elliptical drainage area where the pressure towards the central well gradually decreases, and the flow is characterized as elliptical (Yang et al., 2019).
- Steady state flow is observed when constant pressure is applied to the reservoir boundaries. This pressure can arise from a surrounding aquifer that supports the petroleum system, from injection wells peripheral to the reservoir that provide mass and pressure to the system, or from an expanding gas cap. For a fishbone well, the same elliptical flow pattern applies as in the pseudo-steady state regime.

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4.3 Structural properties that affect productivity

The possibility of using fishbone wells arises after an assessment of the impact on the production of the different configuration of the laterals, but always considering the characteristics of the reservoir. Because of their complex design that causes production interference between the wellbores of the system, specialized models are required to simulate them (Al-Rbeawi & Artun, 2019). The main parameters of these models that have been extensively studied in the bibliography are the following:

- The number of laterals
- The length of laterals
- The angle between the lateral and the main wellbore (azimuth)
- The permeability anisotropy
- The distance between the laterals
- The geometry of the laterals
- The scattering of the laterals

All the above refer to the method of drilling large-scale laterals for the general exploitation of a field and not to the fishbone stimulation method, where the only variable is the number of subs to be used. It is generally accepted that, up to a point, the increase in production is proportionally to the number of subs. The situation in which more subs do not have any benefit was named by Cavalcante et al., 2015 as the “fishbone production saturation point”.

4.3.1 Number of laterals

Numerous studies have shown that the inflow is proportional to the amount branches drilled but there is an optimal number, beyond which additional branches do not contribute significantly to further production growth (Xing et al., 2012). In addition, Lian et al., 2012 stated that the production boost with the increasing number of laterals occurs only in the first phase during the transient flow period and then disappears, which is also reflected in Figure 23 by Xing et al., 2012. Their results however are not in agreement with the findings of Abdulazeem & Alnuaim, 2016. They discovered that the IPR when simulated two laterals was greater than the IPR resulted from fourteen (Figure 24). But that was not the case for the simulation conducted by Ahmed et al., 2016, who found weak a weak correlation (Figure 25).

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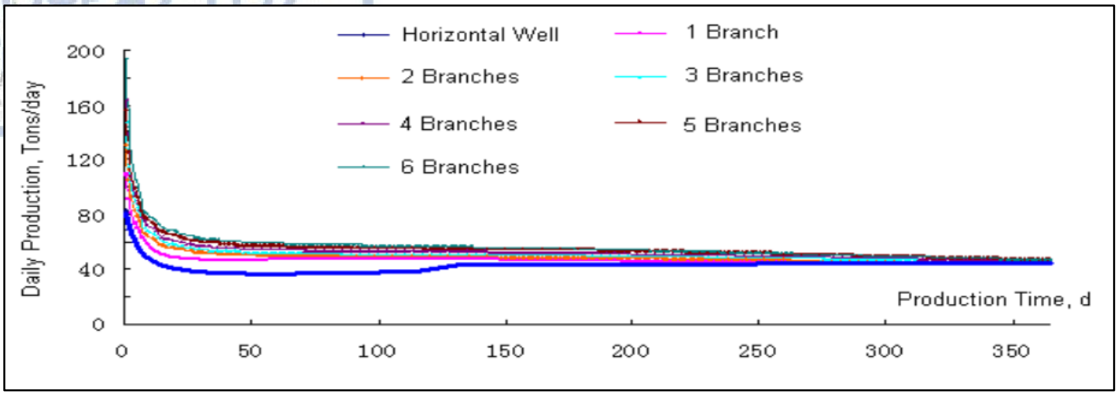

Figure 23: *Comparison of the daily production of fishbone well in relation to the number of laterals, as well as for single horizontal well. (Xing et al., 2012)*

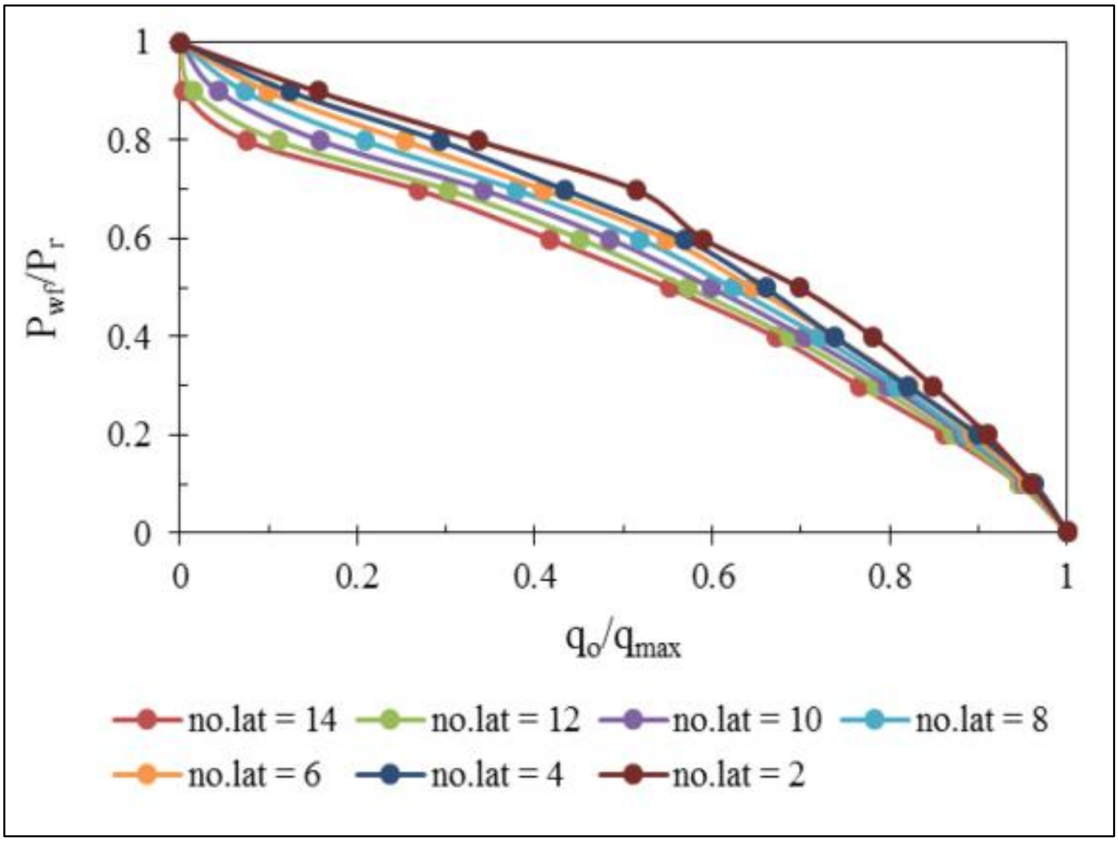

Figure 24: *Comparison of dimensionless IPRs of fishbone well in relation to the number of laterals. (Abdulazeem & Alnuaim, 2016)*

In a study conducted by Ayokunle & Hashem 2016, a 5000 ft main horizontal well was simulated having two to six 200 ft laterals, representing 8% to 24% of its length respectively. It was found that the phenomenon of increased production lasted for less than half a year and

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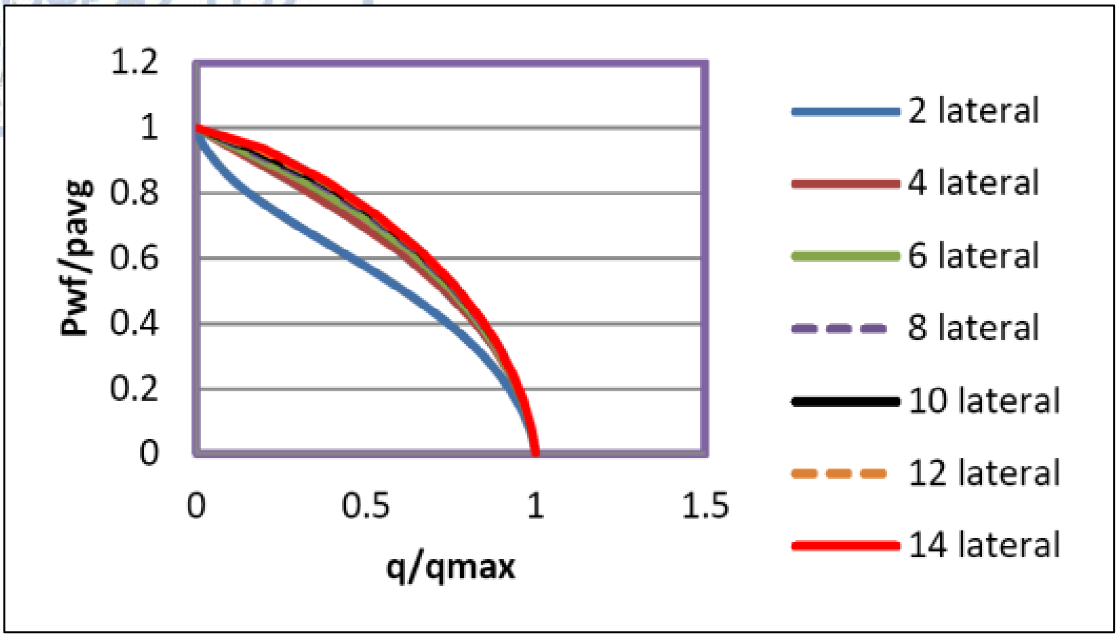

Figure 25: *Comparison of dimensionless IPRs of fishbone well in relation to the number of laterals. (Ahmed et al., 2016)*

before being eliminated, it was gradually reduced in intensity (Figure 26). The well with the two laterals produced initially about 29000 barrels per day while the one with the six started with 33000. This is a 13,79% increase caused by extending the laterals by a length equal to 16% of the main horizontal well, or, in other words, by increasing the total length of horizontal sections by 14,81%. Within two to three months their production volumes were gradually equalized to about 11500 barrels per day. Though, it was suggested that longer laterals may have different effects.

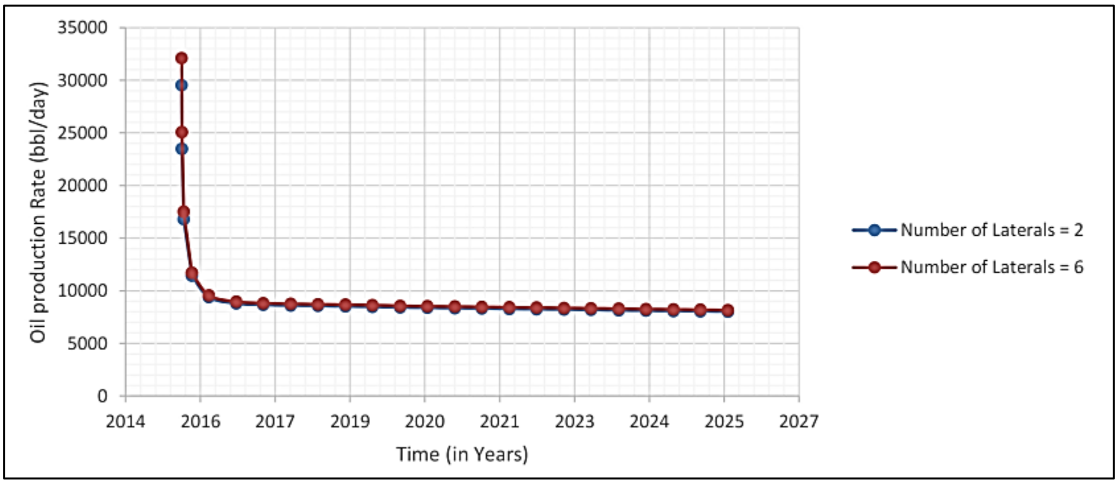

Figure 26: *Long-term oil production rate of a fishbone well consisting of two and six laterals. (Ayokunle & Hashem, 2016)*

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Regarding the percentage participation of the laterals, Al-Rbeawi & Artun, 2019 showed that when there are four laterals with a total length equal to one fifth of the main horizontal well, their contribution to the total production reaches only 22%. When their number is reduced to two while representing the same length, they participate only by 12.5% in the productivity index. In both cases, however, the productivity indices are almost the same. In compliance with that, there is recent evidence from artificial intelligence models that increasing the number of laterals has only a little positive impact on production (Hassan et al., 2019).

However, as Cai et al., 2013 proved, when the length of the main horizontal well is shorter (1312 ft) and the length of each branch (492 ft) represents a big portion of it (37,5%), then the number of laterals is the most important factor that affects productivity. In their research, the difference in production between wells with two and four branches representing 75% and 150% of the main horizontal length was 32,154 m^3/day and 42,901 m^3/day respectively. This is an increase of 33,42% caused by adding laterals of length equal to 75% of the main horizontal well, or, in other words, by increasing the total length of horizontal sections by 42,86%.

In their work, Lux et al., 2016 investigated the effect that different configurations have on the drawdown pressure while suggesting that not only does minimizing the drawdown has a positive effect on production, but also, in reservoirs supported by aquifers, water-coning problems can be delayed. Drawdown pressure is described as the difference between the reservoir pressure and the bottom hole flowing pressure. They discovered that, up to a point, more laterals decrease the maximum drawdown. The effect, however, presented a declining intensity. In radially distributed multilaterals, the trend even reversed which can be attributed to the interaction of the laterals, confirming the findings of other researchers regarding the existence of an ideal or optimal number of branches.

Such conclusions, and specifically for this variable of a fishbone well configuration, can significantly contribute to capital savings, since drilling additional unnecessary laterals is both costly and time-consuming.

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4.3.2 Length of laterals

Regarding the length of each branch, the longer the laterals extend into the reservoir, the more exposure is achieved, and therefore the higher the rate of production (Figure 27). However, maintaining the integrity of the structure by not adopting extreme production scenarios, which in turn lead to the drilling of very long laterals is critical, otherwise integrity issues may arise (Xing et al., 2012). In addition, Ohaegbulam et al., 2017 and Lux et al., 2016 concluded that after a horizontal well reaches a certain length, any further increase does not yield the expected production.

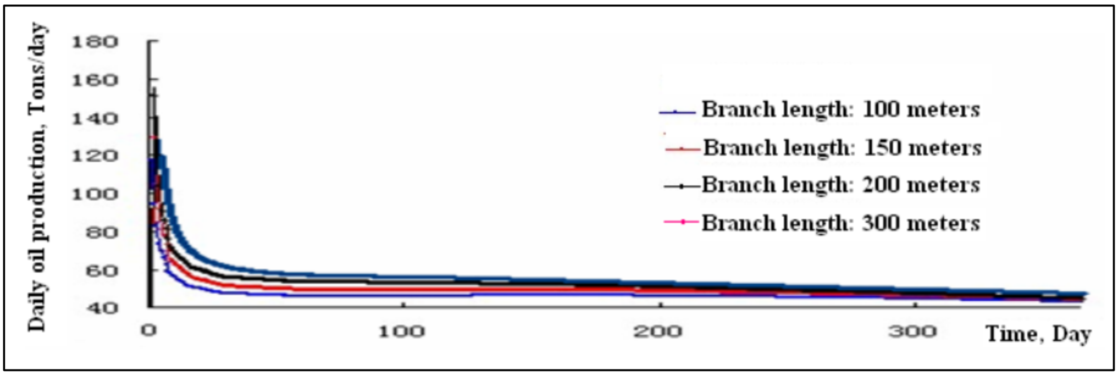

Figure 27: *Daily oil production for different lengths of laterals. (Xing et al., 2012)*

According to Xing et al., 2012, an ideal length is that of 200 meters. In their study, Lian et al., 2012 found that increasing the length of each lateral from 100 meters to 300 meters only influenced the first day of production, during which the reservoir was in the transient flow regime. At this stage, the hydrocarbons are equally distributed throughout the reservoir, so longer laterals can sweep a bigger area. But when this area is depleted, it takes the same effort for the fluid that is far away to flow into a fishbone well that it would be needed if there was just a simple horizontal well. Abdulazeem & Alnuaim, 2016 found minor correlation between the length of laterals and the IPR (Figure 28). Similar results were found from the simulations performed by Ahmed et al., 2016 (Figure 29), who proposed that the deeper the laterals expand, the better the resulting IPR.

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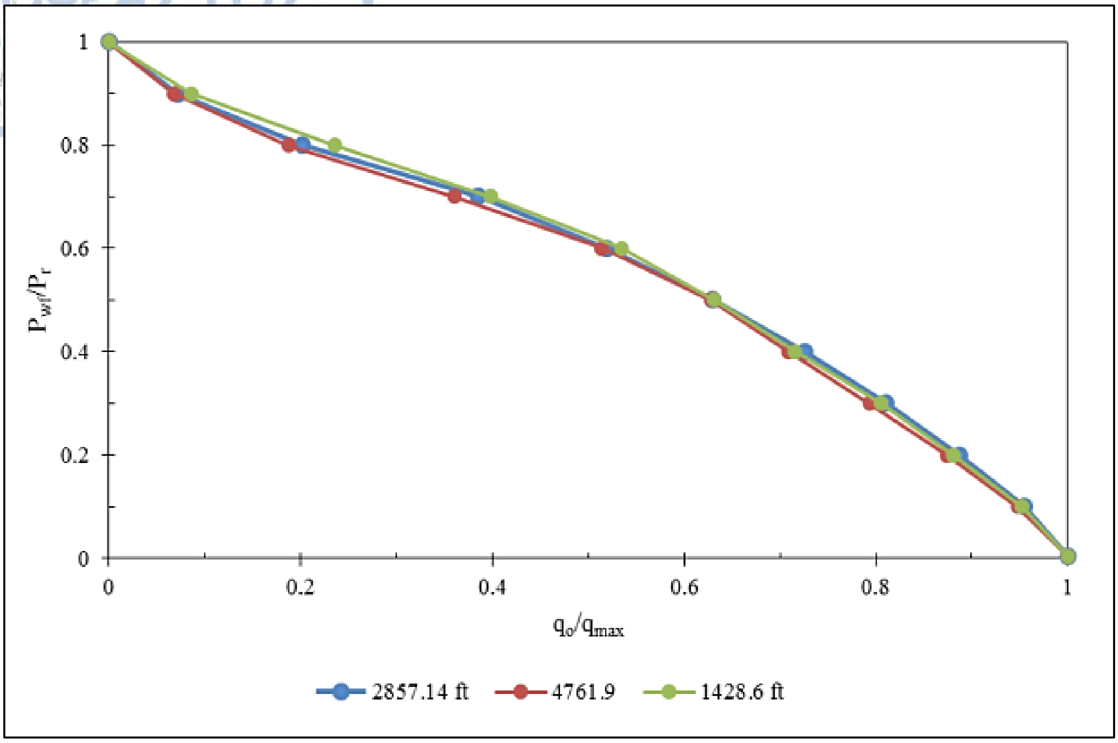

Figure 28: *Comparison of dimensionless IPRs for different lengths of laterals. (Abdulazeem & Alnuaim, 2016)*

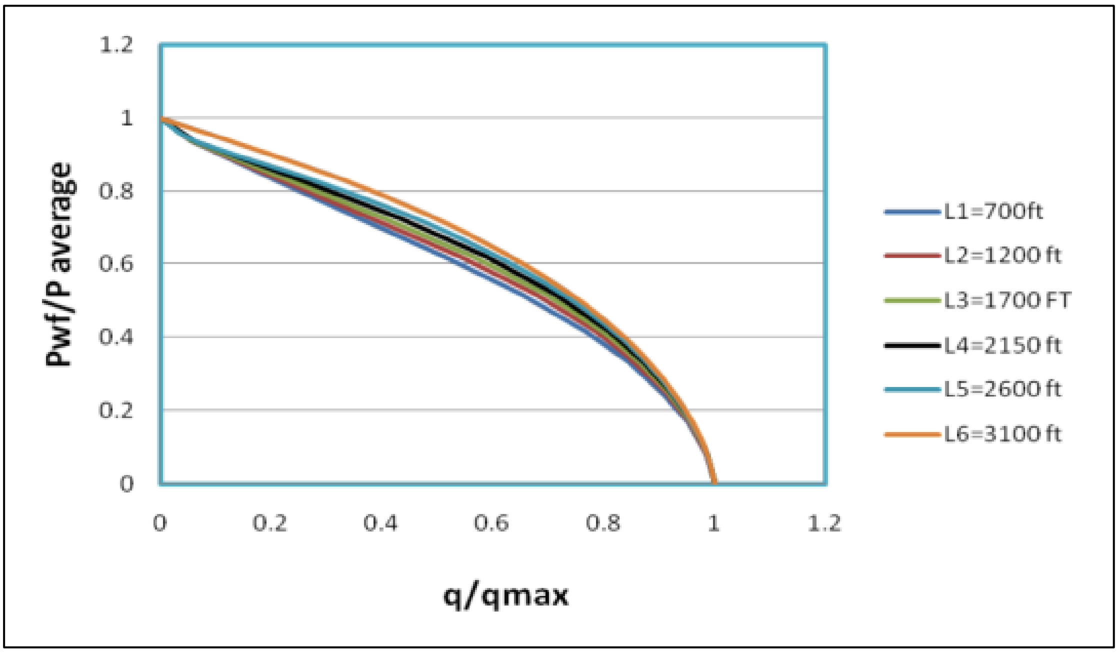

Figure 29: *Comparison of dimensionless IPRs for different lengths of laterals. (Ahmed et al., 2016)*

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4.3.2.1 Heel-to-toe effect

During the production phase, the pressure along a well decreases more and more as fluid flows towards the surface. This is because there are forces that resist the flow, causing the fluid to lose energy continuously. In vertical sections, the main of these forces is gravity.

In horizontal wells, there is a phenomenon called "The heel-to-toe effect". Considering the reservoir pressure along a horizontal section constant, as the fluid flows from toe to heel, it loses energy due to the friction developed with the walls of the pipeline. In Darcy's law, this condition is taken into account through the term L, which represents the length of the pipe, or in other words, the distance traveled. Therefore, there is a greater differential pressure between the reservoir and the inside of the well at the heel compared to that at the toe. For a homogeneous reservoir, not only does this lead to higher inflow at the heel, but problems associated with high inhomogeneous inflow also arise, such as early water and gas breakthrough as shown in Figure 30 (Ohaegbulam et al., 2017). In heterogeneous reservoirs, the problem will affect the areas of increased permeability.

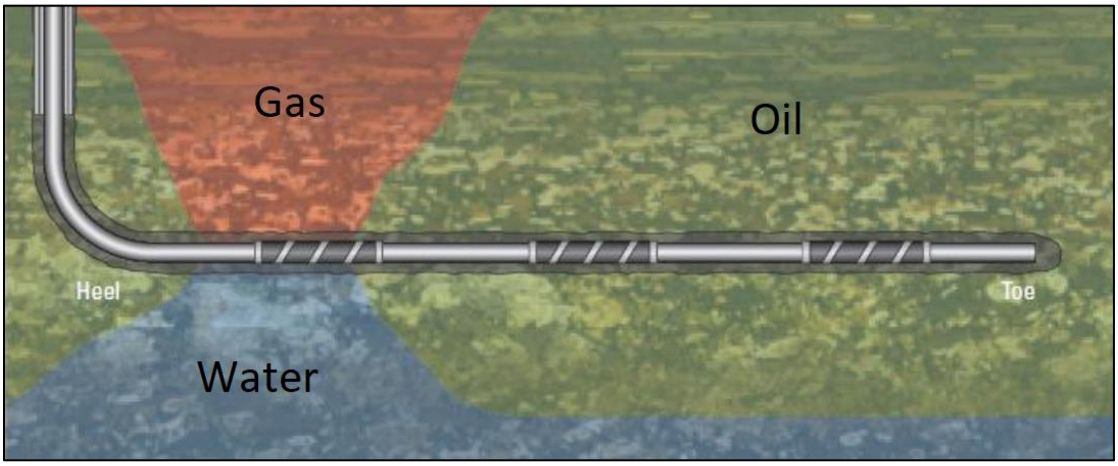

Figure 30: *Demonstration of the "Heel-to-toe phenomenon that causes water and gas coning due to the greater drawdown pressure at the heel of a long horizontal well, which in turn causes higher inflow at the heel compared to that at the toe. (Manish et al., 2015)*

The initial solution that started to be applied was the installation of prefixed downhole passive Inflow Control Devices (ICDs), which could equalize the inflow along the horizontal well but could not prevent the entry of fluids into the production tubing, so the phenomenon was simply delayed (Figure 31). Meanwhile, restricting the inflow in reservoirs with high production capacity would reduce the pressure drop along the well (Ohaegbulam et al., 2017).

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From further development of these devices, Autonomous Inflow Control Devices (AICDs) and Autonomous Inflow Control Valves (AICVs) emerged, which can isolate parts of a reservoir where an inflow of unwanted fluids (e.g., water) is observed (Moghaddam et al., 2013).

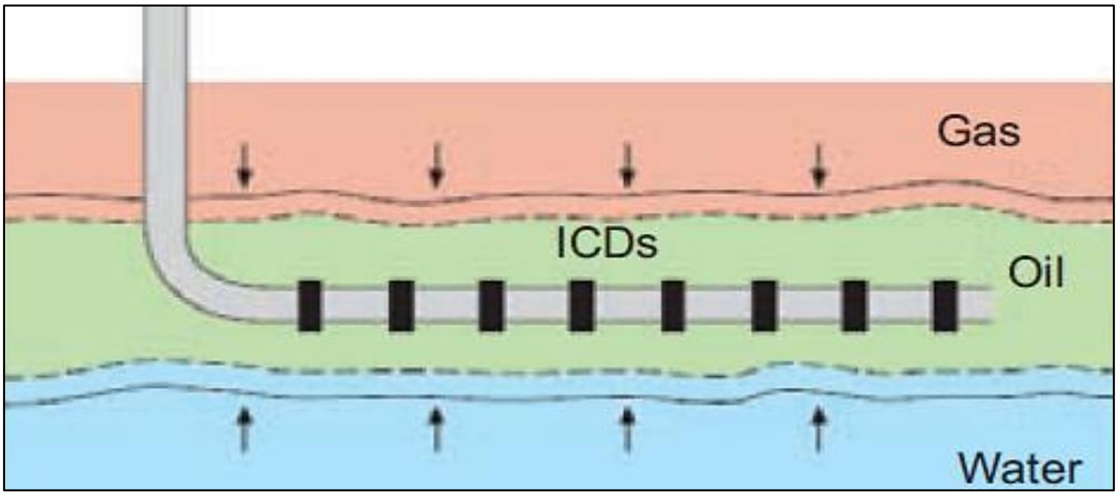

Figure 31: *Prevention of early inflow of unwanted fluids using Inflow Control Devices that balance the inflow along the entire length of a horizontal well. (Manish et al., 2015)*

Finally, since the pressure drop occurs because friction develops as fluids flow into the well, one solution to minimize the phenomenon is to drill shorter ad wider wells so that the hydrocarbons do not travel long distances but, at the same time, without compromising production (Ohaegbulam et al., 2017). Hill & Zhu, 2006 supported this theory especially when it comes to very productive reservoirs of high permeability.

In a fishbone well, the point of lowest pressure according to Yang et al., 2019 is in the area where the innermost laterals join the main horizontal section. Utilizing fishbone wells of high TAML-level can provide the possibility to isolate certain laterals if an influx of unwanted fluids is detected.

In conclusion, proper simulation is needed before the construction of a well to determine the ideal length to avoid early water and gas inflow, or whether drilling a fishbone structure will be more beneficial.

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4.3.3 Angle between laterals and the main wellbore (azimuth)

According to Lian et al., 2012, higher angle between the laterals and the main horizontal well has a positive impact on the output at the transient period due to the resulting greater drainage area. However, for the same reason discussed in the section about the role that the length of the laterals plays, this factor is also not important during the late production phase. It was also suggested that the values remain below 60 degrees, as it was found that the added amount resulting from the extension of the laterals up to 90 degrees relative to the main horizontal well was negligible. Aiming to minimize the pressure drop, Lux et al., 2016 showed that increasing the angle works positively as it further isolates the laterals, but the effect is significantly attenuated after about 60 degrees. Xing et al., 2012 studied a system of four symmetric laterals for four different angles (15, 20, 30, 45 degrees). They concluded that increasing the angle from 15 to 45 degrees, increased the total production by 3,92%, in which the main well participated by 12%, and the laterals by 88%. Increasing the angle from 30 to 45 degrees only resulted in 0.15% increase in production. Therefore, they suggested that the "opening" of the laterals should be between 20 and 30 degrees. In contrast, Al-Rbeawi & Artun, 2019 pointed out that when the azimuth angle is lower than 30 degrees, interaction events occur between the laterals and the main wellbore.

As discussed in the chapter on fishbone drilling, near the junction with the main well there is an interval of high dogleg severity, namely the "ramp-up section", in which the laterals are further separated. The greater the angle between the main well and the lateral, the more the flow of fluid molecules must change as they pass through. So, the more their kinetic energy and pressure will be reduced.

4.3.4 Permeability anisotropy

According to Ahmed at al., 2016 the IPR of a fishbone well relies heavily on the horizontal to vertical permeability variation, even though extreme permeability differences were simulated in their research (Figure 32). Ayokunle & Hashem, 2016 noticed that high vertical permeability increases the productivity of fishbone wells. An explanation could be the greater surface that multiple wells provide for the hydrocarbons to enter from the vertical direction. However, they noticed that, in the case of thin reservoirs the effect fades because of the depletion of the vertical resources. On the other hand, Abdulazeem & Alnuaim, 2016 simulated three ratios of vertical to horizontal permeability with no big differences in the extracted IPRs (Figure 33).

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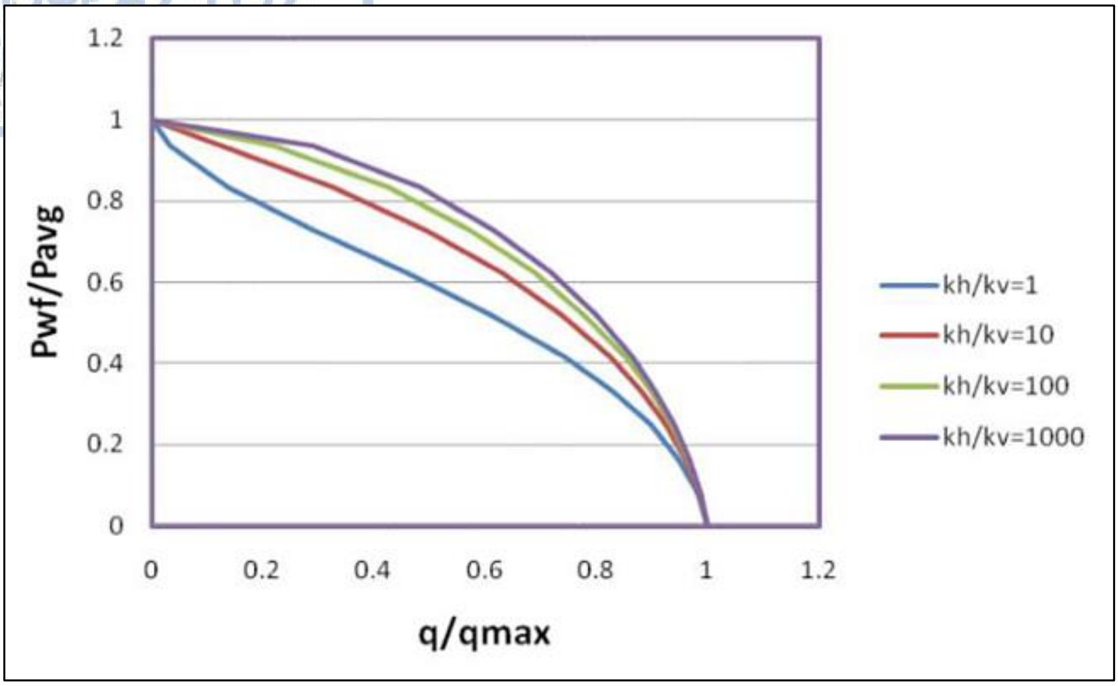

Figure 32: *Comparison of dimensionless IPRs for different horizontal to vertical permeability ratios. (Ahmed et al., 2016)*

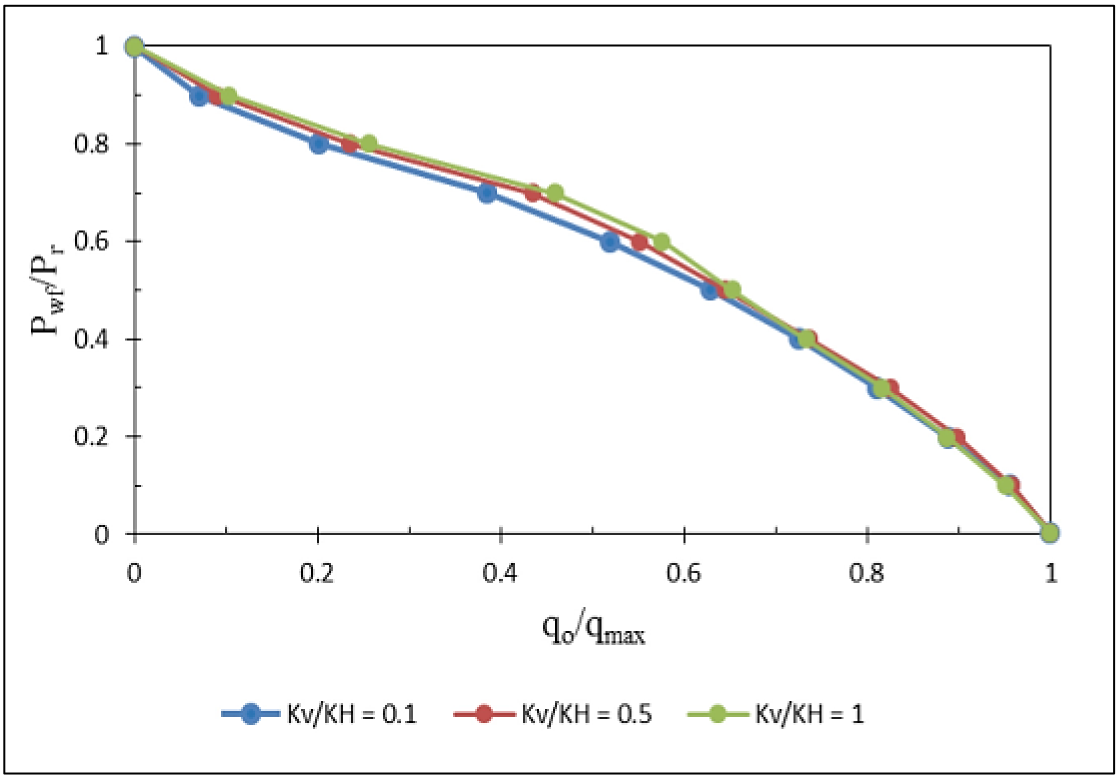

Figure 33: *Comparison of dimensionless IPRs for different vertical to horizontal permeability ratios. (Abdulazeem & Alnuaim, 2016)*

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The use of fishbone wells makes more sense when there is great difficulty in the flow of fluids in the vertical direction. This is the case of reservoirs with inner beds. Deviating from the horizontal plane and penetrating these inner beds is a way of connecting the reservoir's internal flow system, achieving greater exposure. Therefore, the reference of the lateral inclination is a necessary element to make it clear whether they are connected to more horizontal flow systems that exist along the vertical axis. Unfortunately, this is not the case with the published papers that were considered in this dissertation, so no safe conclusions can be drawn.

4.3.5 Distance between laterals

Similarly with the existence of an ideal number of branches, there is also an ideal spatial arrangement that ensures the lowest possible cost but with the best production efficiency for the exploitation of a reservoir. When the branches are close to each other, there is an overlap of the drainage area of each lateral, so not only is the maximum coverage for the predetermined number of laterals not obtained but there is a further pressure drop with the risk of affecting the movement of hydrocarbons within the wells since their kinetic energy is lowered. Xing et al., 2012 suggested an indicative distance range from 80 to 150 meters for an average branch length of 200 meters.

Results from simulations and artificial intelligence techniques revealed that there is only a minor positive correlation between the productivity of a fishbone well and the distance between the laterals (Figures 34 & 35) (Abdulazeem & Alnuaim, 2016; Ahmed et al., 2016; Hassan et al., 2019). Due to this fact but also to reduce the errors from the initial models, there was a tendency to exclude the distance factor from additional confirmatory research (Hassan et al., 2019). However, Abdulazeem & Alnuaim, 2016 stated that interference phenomena due to close distance eliminates the efficiency of fishbone wells.

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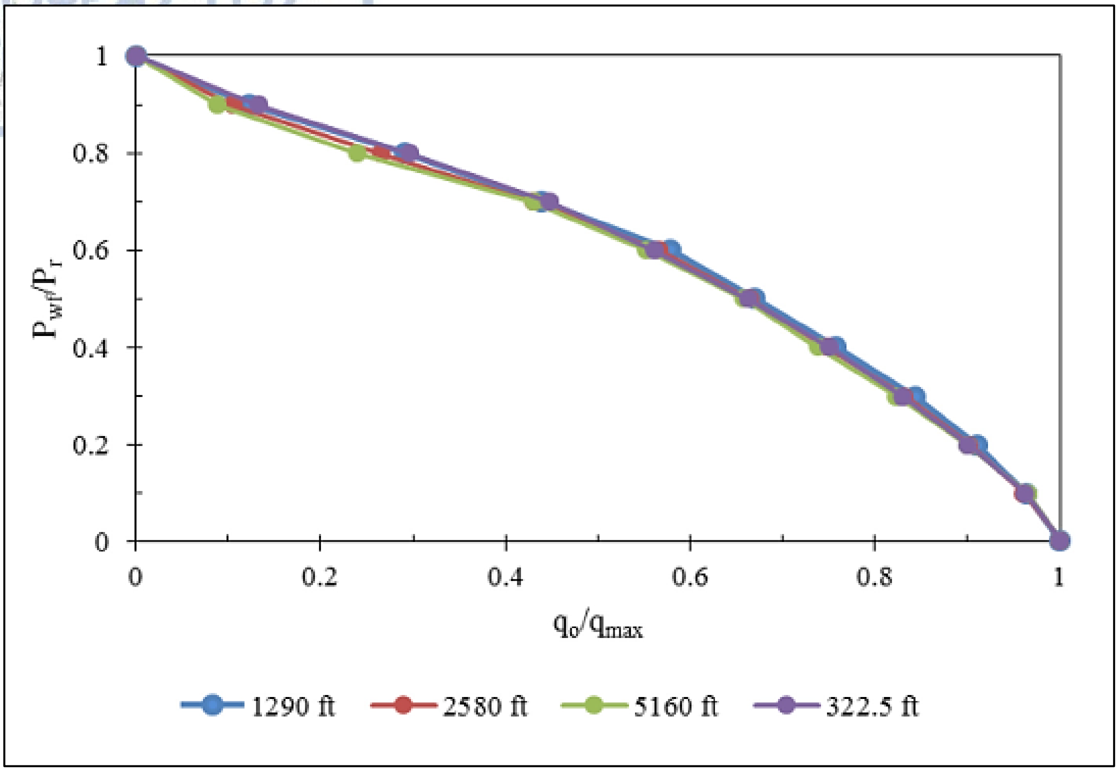

Figure 34: *Comparison of dimensionless IPRs for various distances between the laterals. (Abdulazeem & Alnuaim, 2016)*

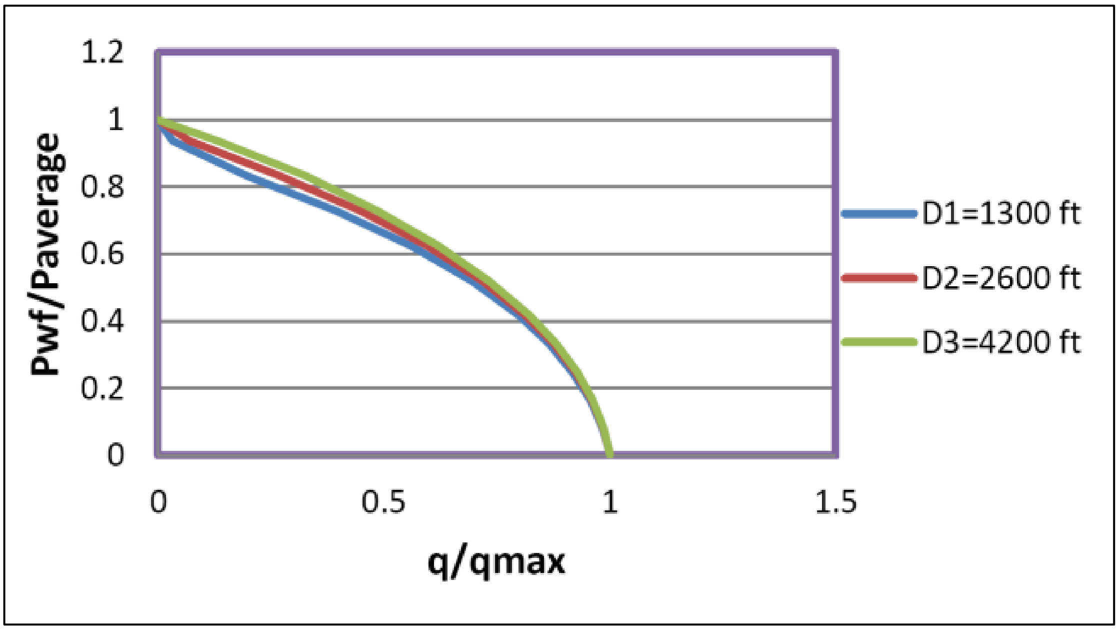

Figure 35: *Comparison of dimensionless IPRs for various distances between the laterals. (Ahmed et al., 2016)*

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4.3.6 Geometry of laterals

According to Yang et al., 2019, wells with complex geometry and continuous curvatures may reduce production as the path that the fluid molecules must follow is not a simple straight line but there are turns where collisions take place which lead to a reduction in their kinetic energy. In their study, they also presented the pressure distribution around the whole structure of a fishbone well (Figures 36, 37 & 38). They concluded that even though the early gas production of curving laterals is higher than the straight, their simulation ended with 18.44% higher cumulative production for the straight laterals (Figure 39). They explained that this was due to the lower pressure losses in the straight laterals and the increased interference of the curving laterals during the late production phase. But the straight laterals caused the production of an extra 13.62% of water. Their results from investigating more complex geometries showed even lower cumulative production of gas but also of water. Therefore, to maximize production, a straight trajectory should be followed when drilling both the main horizontal section and the laterals. Consequently, rotary steerable systems are suitable for this task as they can minimize the tortuosity of a well. It can also be concluded that the fluid

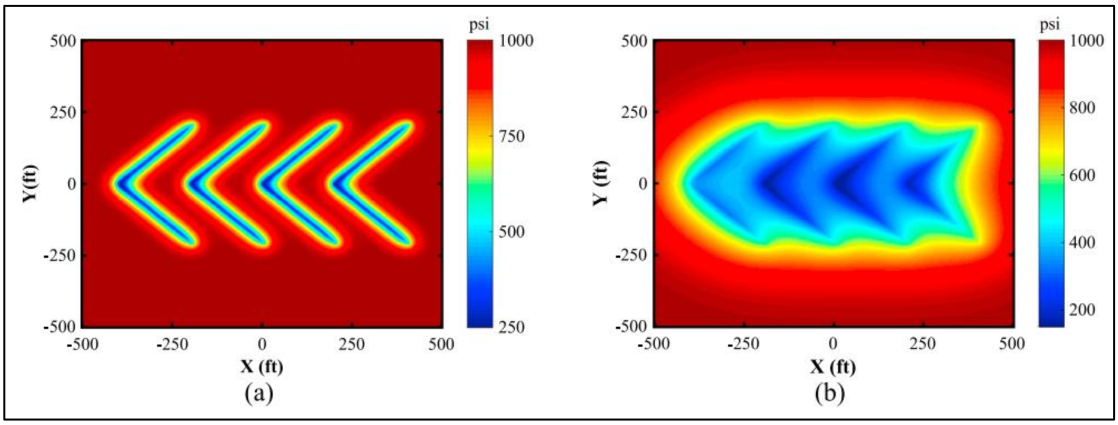

Figure 36: *Distribution of pressure around a fishbone well with straight laterals which produced for (a) 100 and (b) 2000 days. (Yang et al., 2019)*

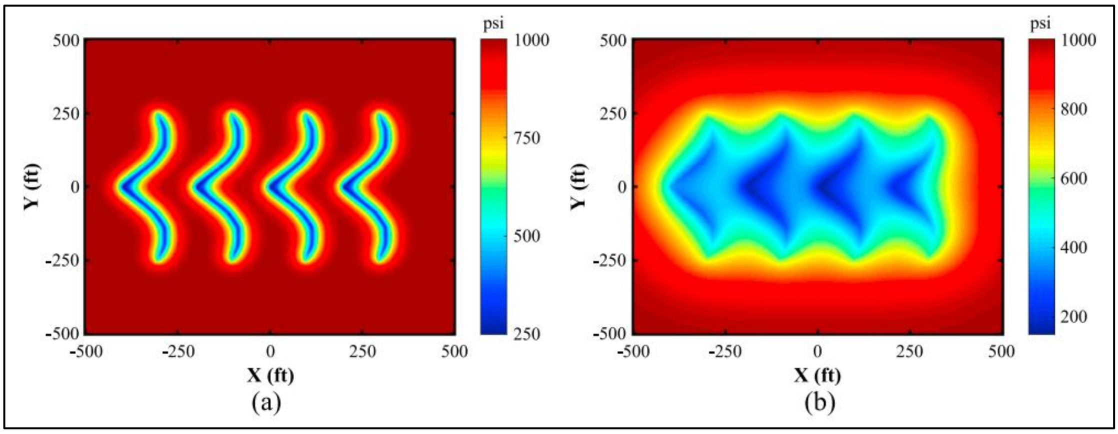

Figure 37: *Distribution of pressure around a fishbone well with curved laterals which produced for (a) 100 and (b) 2000 days. (Yang et al., 2019)*

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inflow calculated from simulating straight laterals is always overestimated because wellbore curvatures are inevitable.

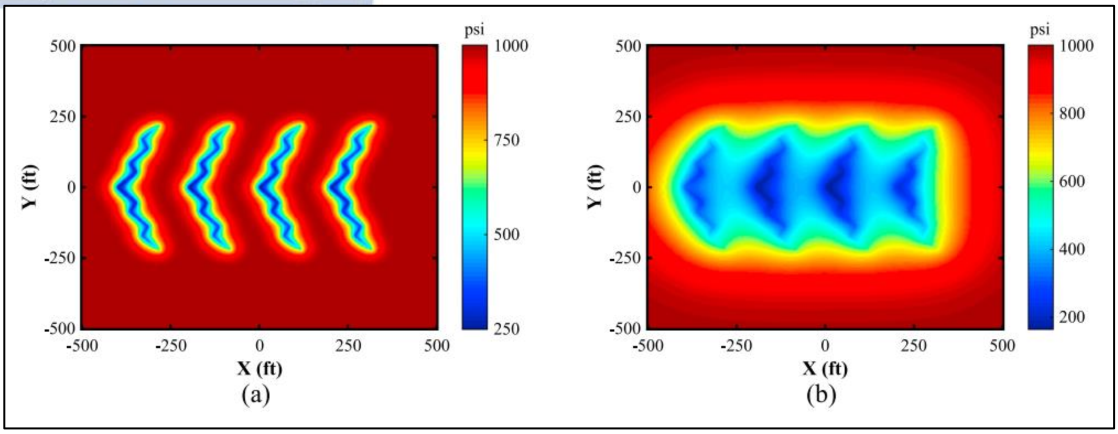

Figure 38: *Distribution of pressure around a fishbone well with "zigzag" laterals which produced for (a) 100 and (b) 2000 days. (Yang et al., 2019)*

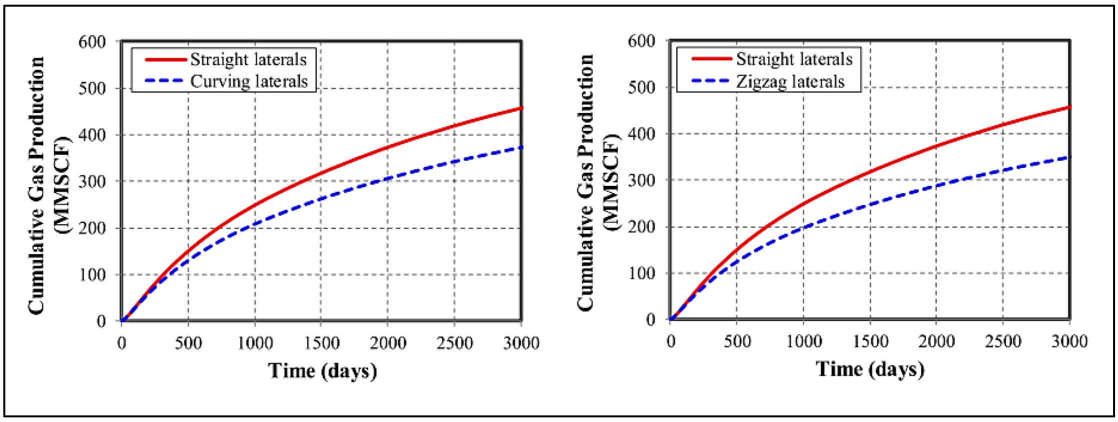

Figure 39: *Comparison of the cumulative gas production of a fishbone well (left) with straight and curved laterals, and (right) with straight and "zigzag" laterals. (Yang et al., 2019)*

4.3.7 Scattering of laterals

It has been found that optimal production is achieved when the branches are scattered in all directions rather than when they are placed on the same side of the reservoir (Xing et al., 2012). In their work, Cai et al., 2013 confirmed that this statement as they found that laterals drilled on both the left and the right sides of a main horizontal well have a slightly higher output than those drilled on only one side (Figure 40). The ideal situation is that of heteronomous branches where there is only one lateral at each junction point that connects it to the main well. The difference, however, between the various lateral positions of every system with the same number of laterals, as can be seen in the Figure, is small.

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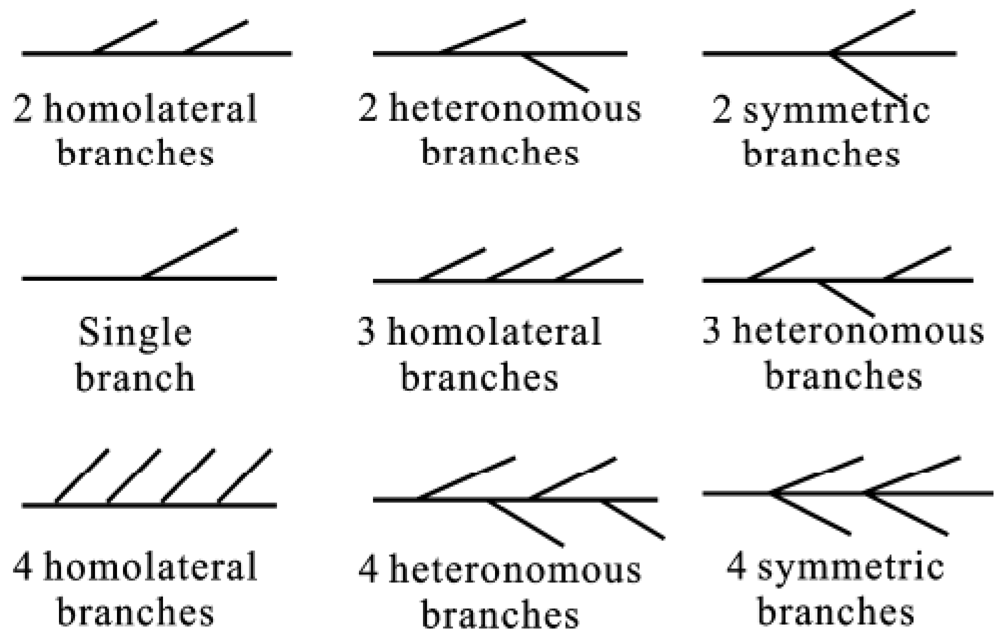

Lateral No.	Homolateral branch	Heteronomous branch	Symmetric branch
1	26.498	—	—
2	31.975	32.154	31.789
3	36.965	37.722	—
4	41.168	42.901	42.32

Figure 40: *Illustration of different layouts that a fishbone well can take with the corresponding output it can yield. Laterals that are asymmetrically scattered along the main horizontal well give the maximum output, but not by a significant difference. (Cai et al., 2013)*

4.4 New empirical IPRs

It is a fact that the Vogel equation is widely used in industry to correlate flow with pressure. However, the multiple factors that govern the structure of a fishbone well, as well as the interactions between them, make it necessary to integrate them into the existing correlation equations. Three such equations will be presented below.

The first was introduced by Ahmed et al., 2016 and was extracted after sensitivity analyses and statistical methods on data that had derived from over 200 simulations. When compared to an IPR generated from a commercial simulation software (Figure 41), smaller amounts of

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gas flow were obtained. But when they applied it to an existing fishbone well, the values they received had a difference of only 4% compared to the actual production. The equation takes into consideration the number of laterals, the horizontal to vertical permeability ratio, and the average length of laterals and is as follows:

$$\frac{q}{q_{max}} = 1 + a\left(\frac{P_{wf}}{P_{avg}}\right)^{b} n^{c} + d\left(\frac{k_h}{k_v}\right)^{e}\left(\frac{P_{wf}}{P_{avg}}\right)^{f} + gL$$

where:

q: the flow for a given bottom home pressure (P_{wf}) in Mscf per day,

q_{max}: the absolute open flow rate in Mscf per day,

P_{wf}: the bottom hole flowing pressure in psia,

P_{avg}: the average reservoir pressure in psia,

n: the number of laterals

k_h: the horizontal permeability in millidarcy,

k_v: the vertical permeability in millidarcy,

L: the average length of laterals in ft.

The terms “a” through “g” are dimensionless constants that were generated by the statistical techniques:

a = 1.056150135

b = 1.35

c = 0.12837

d = -2.49525

e = -0.02782

f = 1.7

g = 2.52E-06

The second equation was developed by Abdulazeem & Alnuaim, 2016 and takes into consideration only the number of laterals, since the results from their research suggested that it is the only factor that affects an IPR. Their methodology followed the same pattern as that of Ahmed et al., 2016, but the only input variable is the number of laterals. The extracted correlation is as follows:

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$$\frac{q_o}{q_{o\,max}} = 1 - (0.0446 * n + 0.1488)\left(\frac{P_{wf}}{P_r}\right) - (0.8288 - 0.0358 * n)\left(\frac{P_{wf}}{P_r}\right)^2$$

Where "n" is the number of laterals.

They considered that their model is aligned with Vogel's correlation for single and dual laterals but as shown in Figure 42, when the laterals are more, there is a deviation.

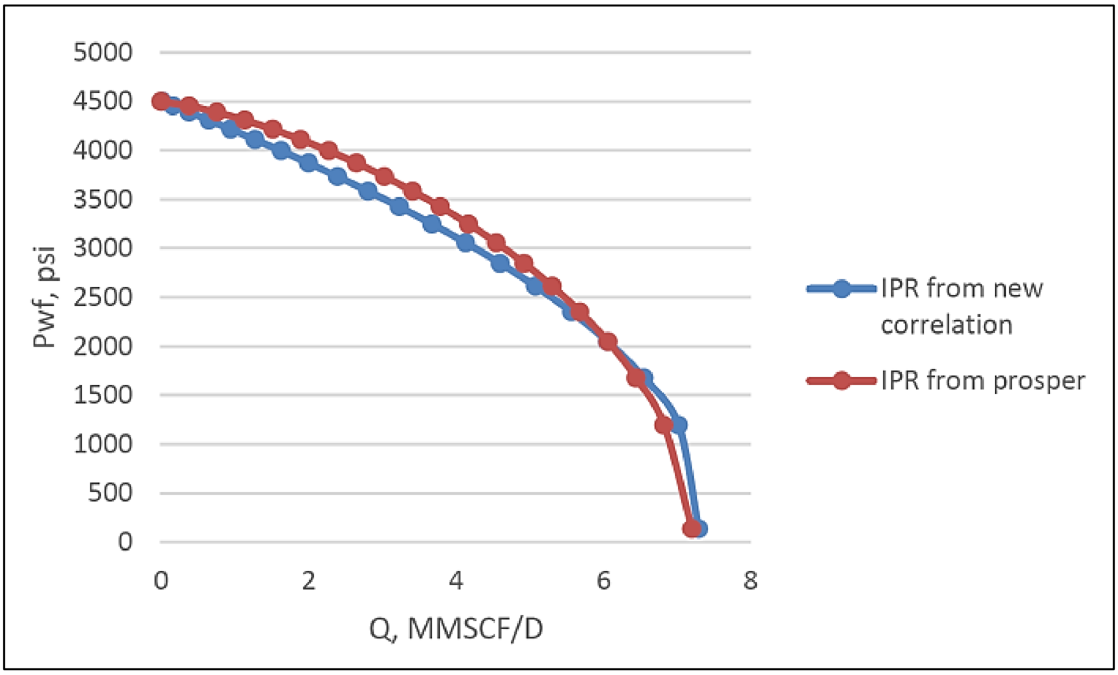

Figure 41: *Differences between IPRs generated from a commercial simulator software and from a new model developed by Ahmed et al., 2016. (Ahmed et al., 2016)*

The final correlation was established by Hassan et al., 2019, who utilized the artificial intelligence method of artificial neural network. They used data sets that had derived from simulations of various configurations and reservoir parameters to create a model, train it and finally test it. At the end, they extracted an equation which, after entering the total length of laterals, the ratio of horizontal to vertical permeability and the bottom hole flowing pressure, can predict the inflow with an error of 7.23%. Figure 43 illustrates a comparison between their model and Vogel's correlation against data from an actual gas well.

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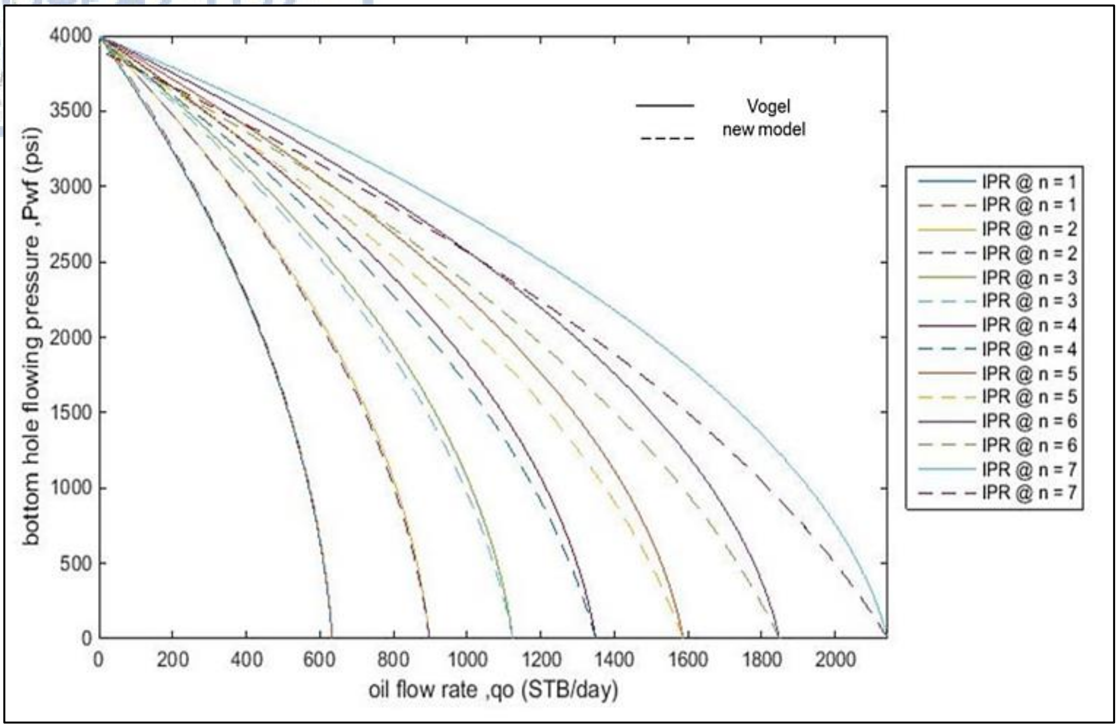

Figure 42: *Differences per number of laterals between Vogel's and a new correlation developed by Abdulazeem & Alnuaim, 2016. (Abdulazeem & Alnuaim, 2016)*

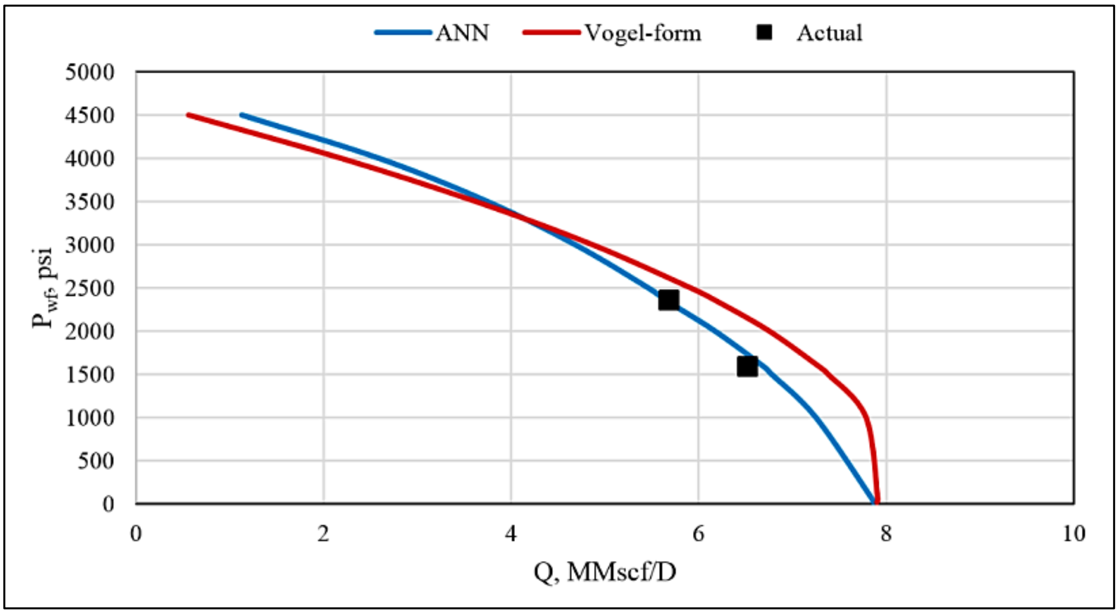

Figure 43: *Differences between the Vogel's and a correlation extracted from utilization of artificial neural network against real inflow data. (Hassan et al., 2019)*

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5. Conclusions

The need to increase production while reducing operating costs, protecting the environment, and exploiting non-conventional reservoirs has led to the adoption of multilateral wells and the development of technology to simplify their drilling. A subcategory of these are the fishbone wells which consist of a main horizontal wellbore and laterals that derive from it, targeting the same reservoir.

Reference to fishbone wells may imply either the method of stimulation where short and small-diameter laterals are drilled, or the larger-scale fishbone wells. These can be drilled either by mud motors, or by the more commonly used rotary steerable systems, which deliver smoother curvatures.

Regarding the stimulation method, the only variable is the number of subs and consequently the number of laterals that may be drilled. It is a decision to be made based on cost-effectiveness analysis and the operating limits of the surface pumps.

In contrast, many factors in the structure of a fishbone well can be determined in large-scale wells. The most frequently studied are the number and length of the laterals, the distance between them and their dispersion along the main horizontal well, the angle they form with the main horizontal section, and their geometry in space. In addition, emphasis is placed on the ratio of the vertical to the horizontal permeability of the reservoir.

According to the literature, the most decisive factors in terms of productivity of these wells are the number of laterals, the angle they form with the main well and their geometry as it has been suggested that straight laterals have a greater inflow. Studies have shown that their length, distance, and scattering do have an impact, but it is not significant.

The role that permeability anisotropy plays is not very clear because it has similar effects on all types of wells. This factor should therefore be studied in more detail and always in relation to the inclination of the laterals, since when they move in the vertical direction, they can be connected to more inner beds, maximizing the exploitation of the usually higher horizontal permeability. There is also disagreement as to whether these factors affect the initial transient period or the entire life of a reservoir.

Nowadays, the scientific community tends to use statistics and artificial intelligence methods to derive new equations - correlations to predict production, since fishbone systems are governed by many factors that interact with each other, complicating simulations.

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