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Review

Deepwater drilling: challenges, evolutions of drilling practice, well design and lessons for Vietnam

Nguyen Quoc Minh[1,2], Luu Thi My Duyen[1,2,3], Huynh Mai Tra[1,2], Le Nguyen Hai Nam[1,2], Tran Trung Dung[1,2,*]

ABSTRACT

This paper provides an overview of the changes in deepwater and ultra-deepwater definitions, the evolutions in drilling rigs, well design, drilling and completion practices, and equipment to overcome many unique challenges and high drilling costs. Oil and gas drilling and development in deepwater and ultra-deepwater have been around for more than 60 years and become more and more important to the global petroleum industry. With each advancement in technology, we can explore and produce hydrocarbons further offshore, at deeper water depths, and thus the definitions of deepwater and ultra deepwater have been repeatedly rewritten. This segment of the petroleum industry has experienced the highest growth and number of innovations thanks to many giant deepwater discoveries turned into productive fields in the Gulf of Mexico, Brazil, North Sea, West Africa, and elsewhere throughout the world. With more and more wells drilled at ever increasing water depth, the drilling challenges, including both natural and operations hazards increase exponentially, which result in more and more stringent technical requirements for a safe operation. These are being met by the rapid and complicated evolution of BOPs and drillships over several generations, optimization of deepwater big bore well design, and applications of drilling and completion, marine navigation, ROV technologies and procedures, and sharing of lessons learned. This demonstrates the industry's continued and focused interest in the process of enabling resources extraction from this environment of deep and ultra-deep water, especially to combat the high risks and high investment costs for deep and ultra-deep water projects, in which drilling cost is the most significant share. In the second section, the paper looks at the hydrocarbon potentials of Vietnam deepwater and ultra deepwater, the current status, and the various challenges, and proposes required steps to enable Vietnam to tap in this vast unexplored hydrocarbon resources.

Key words: Deepwater drilling, evolutions of drilling, well design, deepwater drilling in VietNam, Vietnam deepwater challenges, Vietnam deepwater drilling status, lessons for Vietnam

[1]*Faculty of Geology and Petroleum Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam*

[2]*Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam*

[3]*Office for International Study Programs, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam*

Correspondence

Tran Trung Dung, Faculty of Geology and Petroleum Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam

Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam

Email: dungtt@hcmut.edu.vn

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INTRODUCTION

Deepwater and ultra deepwater definitions

The definitions of deepwater and ultra-deepwater have changed significantly and often with advances in our industry's capabilities and technology. In the 1970s, a water depth above 200m, off the operational limit of jack-up rigs, was regarded as deepwater [1]. In the '70s and '80s, a water depth limit up to 1,000m could be reached with fixed drilling and production platforms [2]. Later in the '90s and early 2000s these depths can be drilled from spars, tension leg platforms, or by using 4th- and 5th-generation semisubmersibles and drillships. Thus, water depths below 800m- 1200m have become "legacy" deepwater, and now considered "mid water depth". In the 2000s, the developments of 6th generation semi-submersibles and drillships further pushed the operational water depth to over 3,000m [2]. And within the last ten years, the latest 7th and 8th generation drillships can operate at water depth up to 3,650m (12,000ft) [3]. Figure 1 shows the development of drillships throughout the years and the ever increasing water depth they can operate.

In this context, we will define "deepwater" for water depths dominantly can only be drilled by semi-submersibles and drillships, currently starting at around 800m - 1,200m (4,000ft). "Ultra-deepwater" is defined for water depths over 2,300m (7,500ft), where new set of drilling challenges emerge that only recent generation semi-submersibles and drillships can handle, for example with the use of Dynamic Position System, dual-derrick technologies.

Drilling rigs for drilling in deepwater

Semi-submersibles and drillships are expensive floating-type rigs equipped with dynamic positioning systems (DPS) that allow them to stay stable, directly

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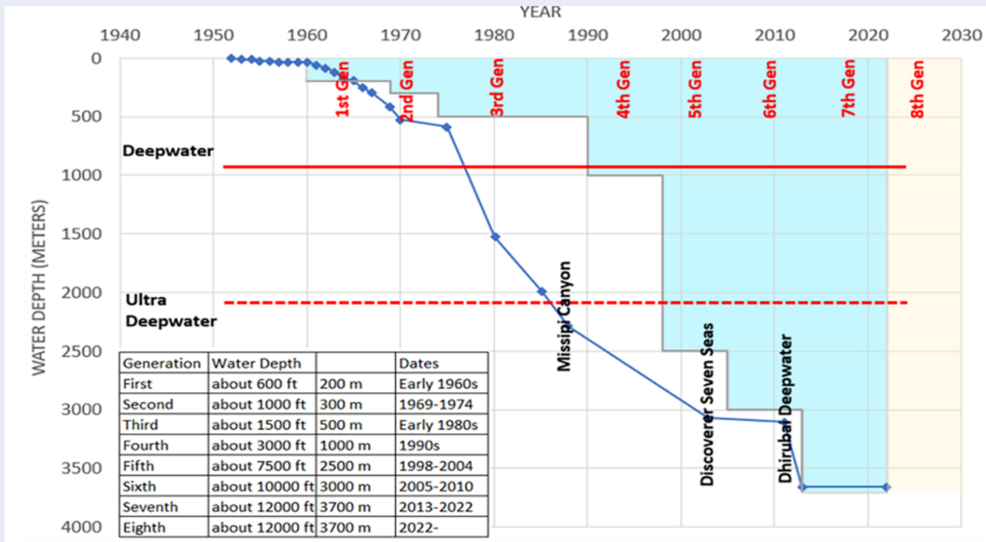

Generation	Water Depth		Dates
First	about 600 ft	200 m	Early 1960s
Second	about 1000 ft	300 m	1969-1974
Third	about 1500 ft	500 m	Early 1980s
Fourth	about 3000 ft	1000 m	1990s
Fifth	about 7500 ft	2500 m	1998-2004
Sixth	about 10000 ft	3000 m	2005-2010
Seventh	about 12000 ft	3700 m	2013-2022
Eighth	about 12000 ft	3700 m	2022-

Figure 1: Evolution of operating water depths with different generations of floating drilling rigs

above the drilling sites against sea currents, winds, and waves, although when operating in shallower water depths the DPS can also be aided by mooring. Rig moves are much faster than fixed drilling rigs. A semisubmersible has legs or pontoons that are partially immersed in water to help the rig's top stay afloat. It has a huge deck space, so big that in 2021 SpaceX bought two decommissioned semisubmersible rigs with plans to convert them into floating launchpads for its enormous 120-meter-tall Starship rockets[4]. On the other hand, a drillship requires no towing and is unique by having a hole in the ship's structure from the main deck through the hull called moonpool. Currently, drillships are the preferred choice for far-flung locations and demand top dollars for their day rate. At the time of writing this paper (Q3/2023), there have been only two 8th generation drillships built and in operation.

Figure 2 shows examples of semi-submersibles and drillships of different generations. Dual-derrick, operating water depth to 3,600m (12,000ft), 40,000ft drilling depth, 15k-20k psi BOP, or hoisting capacity over 2.5 million pounds are some technical attributes that distinguish new generation deepwater drilling rigs to their older generation companions. These specifications allow these drilling rigs to overcome the myriad of challenges when drilling in deep and ultra-deep waters.

Deepwater and ultra deepwater drilling challenges

Although deepwater and ultra-deepwater drilling segment has matured quickly and these wells have rapidly become a significant contributor of the world oil and gas supply (10.4 MMBOE/day in 2022) with an expected 60% growth to over 17 MMBOE/day by the end of this decade[6], there are huge inherent challenges that are unique to its environment. Some of the unique challenges, by no means exhaustive, can be categorized as follow:

Natural hazards

From risks to marine life with seismic acquisitions, subsea operations in deepwater and ultra-deepwater involved no natural visibility, changing currents at different depths, low temperature-high pressures near the seabed, all of which are not as frequently encountered as in shallower water depth.

The total darkness of deepwater can be overcome by using remotely operated vehicles (ROVs) to provide lights and visual support. However, even with ROVs being deployed, the cuttings released to the seabed while drilling the first riserless sections can cause mud clouds that totally obscure the view of the wellhead for a significant period of time.

A current above 2 knots (3.7 km/h) can cause many problems[7]. Currents can cause vortex induced vibrations (VIV) to the drilling riser, make wellbore reentries and setting subsea blowout preventer (BOP) and lower marine riser package (LMRP) and Christmas tree operations difficult and extremely risky to

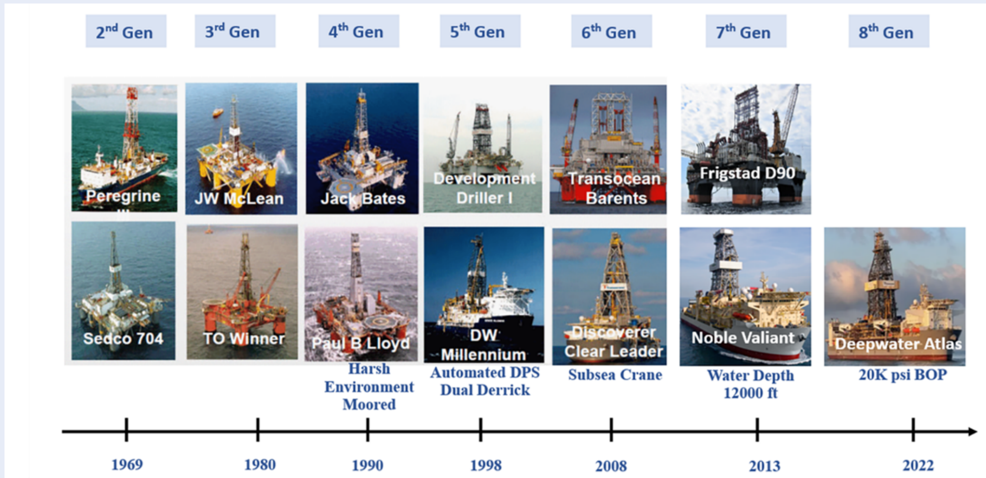

Figure 2: Notable semi-submersible drilling rigs and drillships (modified from [5])

the integrity of the well. An unplanned drive-off might occur as the drilling rig loses its ability to keep its position above the drill site. In the worst case, this will require an emergency disconnect (ED) to separate the wellhead from the drilling rig. However, normally only near surface current velocity and direction are recorded by the monitoring system.

The shallow layers below the sea bed are commonly unconsolidated or very weakly compacted. Under low effective stress, shallow water flows (SWF) can occur during the riserless drilling sections, especially with jetting operations. This geohazard can severely affect the integrity of the deepwater hole being drilled.

Finally, for deepwater and ultra deepwater, the hydrostatic pressure is very high, while the water temperature is very low (around 4°C, or 39-40°F). These low temperature-high pressure conditions are conducive to the formation of hydrates, which in turn can easily plug the drilling pipe and/or subsea BOP.

Operational hazards

The construction of a deepwater and/or ultra deepwater well also poses many technical challenges besides the natural hazards. The vast distance between the drill site and shore, ocean winds, and high seas make logistics arrangements from the supply base very difficult. For efficient operations at remote locations, drilling rigs are required to be self-reliant with as much supply stocked and ready as possible. Moreover, the distance also negatively affects emergency responses.

The deeper the water, the longer and heavier the drill string, the casing string, and the riser become. Respectively, they in turn require higher drill pipe specifications, using heavier landing strings, and equipping riser tensioner with higher capacity to handle the higher tensile loads.

The high pressure, low effective stress conditions mean the required BOP pressure rating to guarantee safe drilling operations is also very high. The standard BOP rating of deepwater well control system is 103 MPa (15k psi) for 7th generation drilling rigs, and 138MPa (20k psi) for the newest 8th generation drillships. Figure 3 shows the evolution of the subsea BOPs over the years, with the current size and weight being almost triple the size and weight of BOPs 20 years ago.

All these additional weights, from riser, BOP, and casing results in new axial load bearing capacity and bending moment requirements for the well foundation, namely the conductor and surface hole sections. The standardized size of conductor casing has dominantly become 91.44 cm (36 inches) with setting shoe depths ranging from 250 ft to 300 ft BML. Despite this setting, many deepwater and ultradeepwater wells still failed and had to be abandoned due to instability because the well total weight exceeded the conductor casing loading capacity [9,10].

Finally, in order to save tripping times for operations like bit changes, running in casing, dual-derricks that allow dual activities were developed since the 5th generation drilling rigs. For safe and efficient operations at this level of complexity, crew competency and communication among drilling crew - marine crew - and ROV crew are essential.

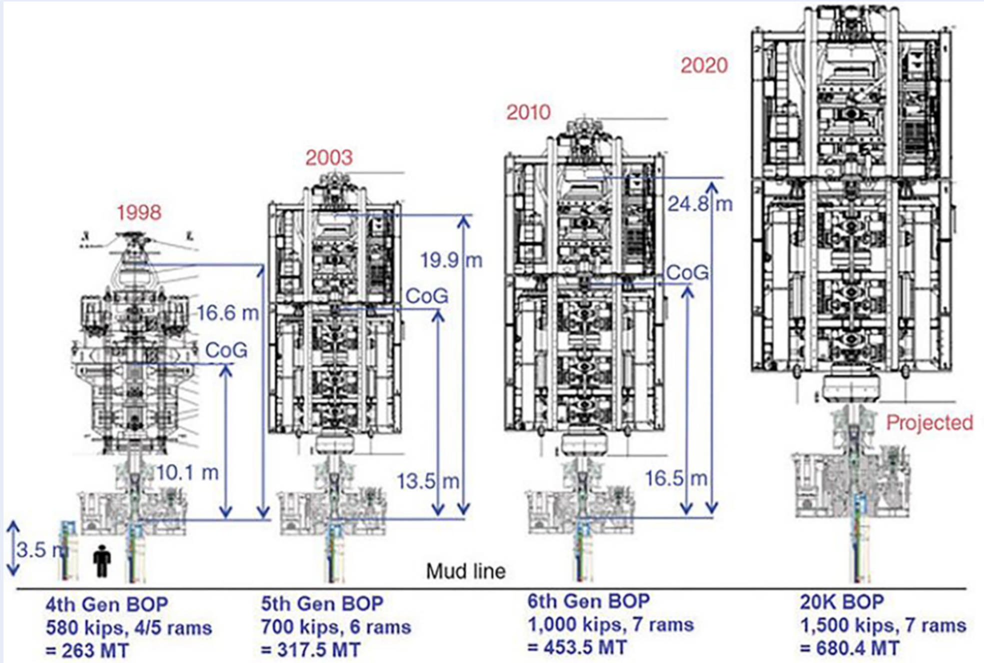

Figure 3: Deepwater and ultra deepwater subsea BOP and LMRP size and weight change over the year [8]

Deepwater drilling cost

In order to overcome these aforementioned challenges, operators have to pay prices at the highest level to drill wells in deep- and ultradeep waters. The majority of the total well cost is the day rate paid to the drilling contractors for the services of their top-of-the-art drilling rigs and crews. The remainder is costs for site survey, rig moves, tangibles, intangibles, and miscellaneous items. While shallow water wells may allow loggings and completions to be done offline (e.g. by utilizing a much cheaper intervention and completion unit (ICU) placed on a service vessel), for deep and ultra-deepwater, all activities, from dry-hole drilling, formation evaluation, to completion need to be done with the drilling rig. Therefore, the total cost can be up to 100 million dollars for a well. This great cost depends heavily on the time to drill the well, and especially the dayrate.

The time to drill a well depends on the rig move, the total drilling depth and well complexities. Rig move refers to the relocation of the drilling rig to the drill site, which might require moving across the oceans. With the latest generation rigs, the total drilling depth can be more than 12 km (40,000 ft) long. Coupled with complex well designs to overcomes various drilling challenges, drilling operations could take a few months to reach the well's target depth. The famous and ill-fated Macondo well took BP more than six months and two rigs to drill and complete, before the blowout occurred and resulted in a massive disaster to the well, the drilling rig Deepwater Horizon, the drilling crew, and the natural environment of the Gulf of Mexico [11].

The day rate for drilling rigs capable of drilling ultra-deepwater wells is the highest compared to other types of drilling rigs. In the early 2010s when 7th generation rigs just came out, operators might have had to pay a day rate at around 1 million US dollars a day. The day rate plummeted during Covid-19 pandemic, as oil demand and oil prices dropped to record levels, prompting companies to cut production, stop drilling as deepwater and ultra-deepwater prospects became uneconomic [12]. Figure 4 shows the average day rates and total contracted utilizations of drillships and semisubmersible that are capable of drilling ultra-deepwater wells in the last three years [13]. The average day rate for an ultra-deepwater drillship fell below 200 thousand US dollars in late 2020 and early 2021 while day rates for a semi-submersible were lower than 150 thousand US dollar. However, the day rates have bounced back strongly since then, reaching close to 500 thousand US dollars a day in the latest reports [13]. As day rate accounts for approximately half the total cost to drill the well, similar wells can have very different cost, depending on the oil price forecast when

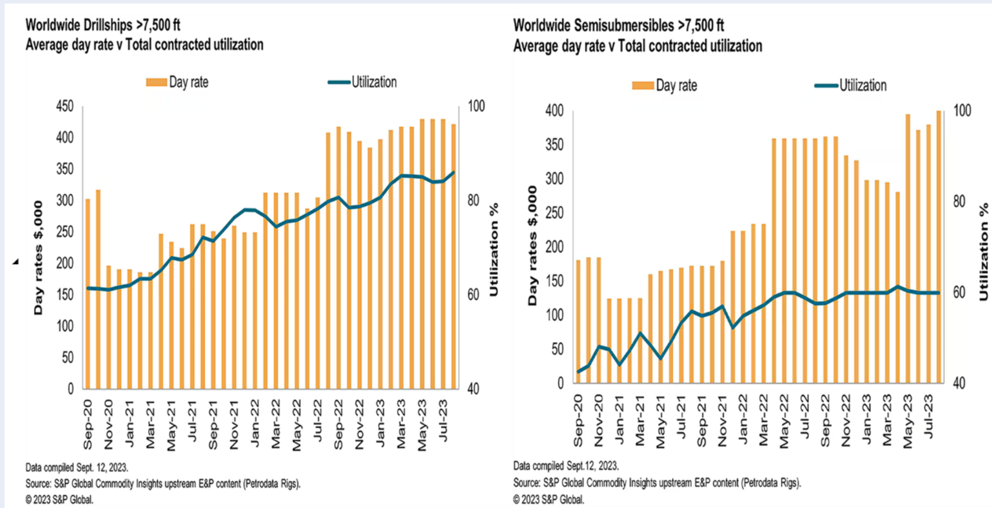

Figure 4: Day rates of most complex drillships (right) and semi-submersible (left) capable of drilling ultra-deepwater wells

an operator signs the drilling contract and how many idle rigs are available at that time.

Deepwater well designs

The high well cost is one of the main contributors to the high break-even prices for deepwater and ultra-deepwater projects. As a result, deepwater and ultra-deepwater projects that are worth considering must have significant reserves to justify development. Then, the development strategy is that only a few numbers of development wells in a deepwater and ultra-deepwater field will be drilled to drain the reserves, in the shortest possible time. The number of producers is significantly less compared to those in onshore and/or shallow waters. Therefore, deepwater and ultra deepwater wells must be designed that allow high drawdown for high production rates[14]. In Brazil, Petrobras is currently producing 2.2 million barrels of oil equivalent per day from 152 deepwater wells targeting pre-salt reservoirs[15], or an average of over 14 thousand BOEPD per well. Another strategy to save drilling cost is that, when an exploration deepwater well is found to be successful, operators would very frequently employ the temporary abandonment practice so that the well can be re-completed and turned into a producer once the production system is ready. As a result, the well designs are quite similar between exploration and development (production) wells.

The high production rate requirement leads to the development and adoption of big bore well designs for deepwater and ultra-deepwater wells. Designing the well from the bottom up, the smallest hole section at the bottom will need to accommodate a production casing string or liner whose diameter is at least 24.45 cm (9 5/8 inches). Above that, a varying number of intermediate casing or liner sections would then have diameters between $11\frac{3}{4}$" to 18", isolating and protecting the well from problematic zones like salt, weak, and/or overpressured formations. Finally, at the top, two (sometimes three) sections of conductor and surface casings are needed to serve as the well foundation. The standard deepwater conductor casing therefore is 36 inches in diameter, while diameters of surface casings vary from 20 to 28 inches[9,10,16–18]. These diameters are 1.5 to 2 times bigger than typical conductor and surfaces casings for onshore wells.

The standard, normal design for Gulf of Mexico deepwater wells has 6-7 casing-liner sections while for deeper wells, tight-clearance designs with 8-9 sections might be required[17]. For reservoirs that are only 1,000m (3,300ft) below mudline, a "slimhole" design with 3 hole sections can be adopted[16,19]. Figure 5[19] shows different well designs for ultra-deepwater wells in Brunei, South China Sea, highlighting the innovations to simplify well structure to reduce the well cost.

To complete deepwater and ultra deepwater wells, cased hole fracpack (CHFP) is the preferred method as it can provide long-term protection to the boreholes, especially when the producing reservoirs are weakly consolidated or unconsolidated[20]. For more competent reservoirs, open hole gravel pack (OHGP) and open hole fracpack (OHFP) options are sometimes considered, as they allow higher rates and reduce completion time and cost[21]. However, when ei-

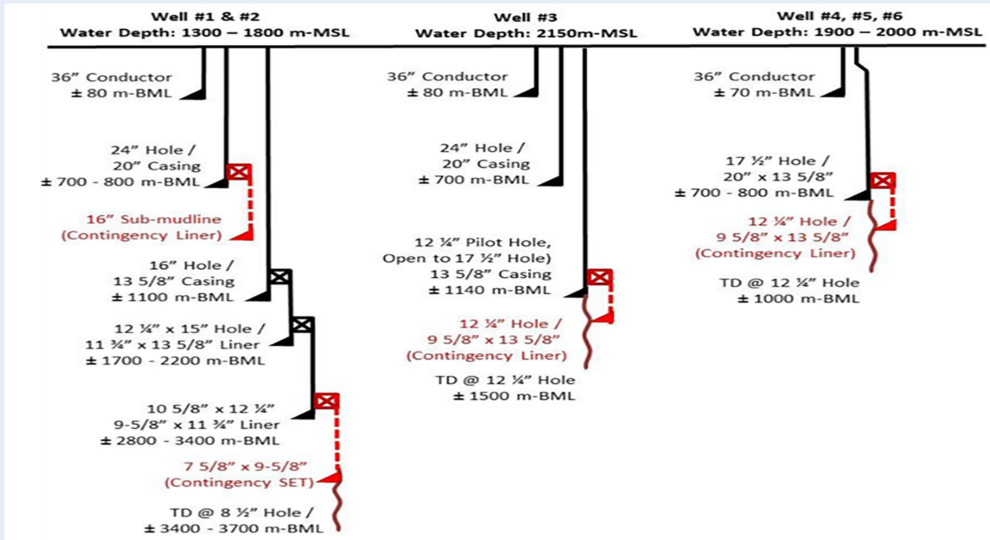

Figure 5: Casing configuration for deepwater wells in Brunei [19]

ther open hole completion method is chosen, the risk of wellbore instability must be carefully evaluated.

VIETNAM DEEPWATER POTENTIAL AND CHALLENGES

Vietnam deepwater basins and oil and gas exploration status

In Vietnam, there are several sedimentary basins with vast unexplored deepwater areas, namely Phu Khanh basin, Tu Chinh-Vung May basin, Hoang Sa basin and Truong Sa basin. The U.S. Energy Information Administration, in 2019 estimated that Vietnam oil and gas proved and probable reserves stand at about 3.0 billion barrels of oil and 20 trillion cubic feet of gas [22]. However, undiscovered resources in deepwater areas can be much greater.

In these four deepwater basins, both well and seismic data are sparse. Most recently, 14,500 line km of multi-client 2D seismic, gravity and magnetic data were acquired for Phu Khanh basin in 2008, which helped enable exploration studies and very first deepwater drilling activities in this basin [23]. The first Vietnam true deepwater well TB-1X at over 1,600m water depth, was drilled in 2015 in block 131 but it was unsuccessful in finding commercial oil or gas accumulations. The other well, TD-1X in block 130, was drilled at over 1,000m water depth and was also a dry hole. Thus, deepwater hydrocarbon potential assessments still rely mainly on interpretations of available seismic lines from which major sequences and structures have been identified.

In Phu Khanh basin, basin studies and recent well results in shallow water have confirmed its positive hydrocarbon potentials, with oil presence and existence of both structural and non-structural traps [24,25]. Shallow gas signatures from seismics data have also been identified and interpreted as hydrate sources in the deepwater areas - the eastern part of the basin [26].

Tu Chinh-Vung May basin has a large region where water depth exceeds 1,000m, but only a handful of 2D seismic lines are available for the deepwater regions [27]. In Hoang Sa basin, many gas fields, including several giant deepwater fields in over 1,500m water depths were discovered and developed illegally by China [28,29]. In Truong Sa basin, little exploration activities were conducted due to tense maritime dispute among countries in the region.

Vietnam deepwater challenges

Nowadays, advanced deepwater and ultra-deepwater technologies and know-how are dominated by the United States, Brazil, and Norway, while China is catching up very quickly with massive investments over the last ten to fifteen years. On the other hand, at this point, Vietnam's capability on its deepwater is still very limited. There is a total lack of experience, facilities, and understanding of deepwater and ultra-deepwater technology. Seafloor topography, shallow soil conditions, sea waves and currents patterns, hydrates accumulations, as well as and prediction of extreme weather conditions like typhoons are things that need to be studied further for deepwater areas.

In order for Vietnam to reverse the situation, governmental strategy, policy as well as financial supports are clearly needed. Deepwater surveys and 2D and 3D seismic acquisitions will be needed in order to have a better estimation understanding of the environment and the subsurface of these basins. Facilities such as geological survey vessels, supply vessels, floating drilling rigs (semi-submersibles and/or drillships), construction yards and bases for maintenance and supply will need to be established. Finally, international partnerships, collaborative academic and industry research in deepwater technologies, from exploration, drilling and completion, to flow assurance, development strategies, from design to operations should be encouraged and pursued.

CONCLUSIONS

The definitions of deepwater and ultra-deepwater have progressively evolved in the last fifty years, and this segment's contribution and importance to the world oil and gas supply have been increasing at an exponential rate. Modern floating drilling rigs - semi-submersibles and drillships - are currently at their 7th and 8th generations, and are capable of drilling wells at locations up to 12,000ft in water depth. To overcome its various challenges and expensive drilling costs, many of which are unique only to deepwater and ultra-deepwater, a completely new line of technologies for well structure (big bore system), safety measures (15k-20k BOP), subsea equipment and drilling-completion-production practices have been developed and continuously refined.

Vietnam has four deepwater and ultra-deepwater basins with large unexplored areas and high estimates of undiscovered resources, although dry deepwater wells were drilled in Phu Khanh basin. At the moment, Vietnam's capability in deepwater oil and gas segment is severely limited, and it would require a total collaborative effort from the government, the industry, the academia to reverse the situation.

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CONFLICT OF INTEREST

The authors certify that this article is a research work of the authors and has not been published elsewhere. It did not copy previous research articles; There is no conflict of interest for any individual, any agency or organization.

AUTHORS' CONTRIBUTION

The article ideas were contributed and supervised by Trung Dung Tran. Le Nguyen Hai Nam provided guidance and analyzed solutions suitable for Vietnam. Nguyen Quoc Minh, Huynh Mai Tra and Luu Thi My Duyen collected data, did analyses, and wrote the manuscript.

All authors have read and approved the final manuscript.

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Bài tổng quan

Khoan nước sâu: những khó khăn thách thức, sự phát triển của công tác thi công khoan, thiết kế giếng và các bài học cho Việt Nam

Nguyễn Quốc Minh[1,2], Lưu Thị Mỹ Duyên[1,2,3], Huỳnh Mai Trà[1,2], Lê Nguyễn Hải Nam[1,2], Trần Trung Dũng[1,2,*]

TÓM TẮT

Bài viết này cung cấp cái nhìn tổng quan về những thay đổi trong định nghĩa nước sâu và nước siêu sâu, sự phát triển của giàn khoan, việc thiết kế giếng, công tác khoan và hoàn thiện giếng, cũng như các thiết bị để vượt qua hàng loạt khó khăn thách thức đặc thù và chi phí khoan cao. Việc khoan và phát triển dầu khí ở vùng nước sâu và nước siêu sâu đã tồn tại hơn 60 năm và ngày càng trở nên quan trọng đối với ngành dầu khí toàn cầu. Với mỗi tiến bộ trong công nghệ, chúng ta có thể khám phá và khai thác hydrocacbon ở xa hơn, ở độ sâu nước sâu hơn, và do đó định nghĩa về nước sâu và nước siêu sâu đã được viết lại nhiều lần. Phân khúc này của ngành dầu khí đã có mức tăng trưởng và số lượng đổi mới cao nhất nhờ nhiều phát hiện dầu khí khổng lồ ở vùng nước sâu và phát triển chúng thành các mỏ khai thác ở Vịnh Mexico, Brazil, Biển Bắc, Tây Phi và nhiều nơi khác trên khắp thế giới. Việc ngày càng nhiều giếng được khoan ở độ sâu ngày càng tăng khiến các thách thức khoan, bao gồm cả các mối nguy hiểm tự nhiên và vận hành đều tăng theo cấp số nhân, dẫn đến các yêu cầu kỹ thuật ngày càng nghiêm ngặt hơn để vận hành an toàn. Những điều này đang được đáp ứng bởi sự phát triển nhanh chóng và phức tạp của hệ thống chống phun trào BOP và tàu khoan qua nhiều thế hệ, tối ưu hóa thiết kế giếng khoan nước sâu với thân giếng lớn cũng như các ứng dụng khoan và hoàn thiện, điều hướng hàng hải, công nghệ và quy trình vận hành các thiết bị điều khiển từ xa ROV, cũng như việc chia sẻ các bài học kinh nghiệm. Điều này thể hiện sự quan tâm không ngừng của ngành dầu khí cho phép khai thác tài nguyên từ môi trường nước sâu và siêu sâu , đặc biệt khi phải đối mặt với rủi ro cao và chi phí đầu tư cao cho các dự án nước sâu và siêu sâu, trong đó có thể kể đến chi phí khoan rất cao. Trong phần thứ hai, bài viết xem xét tiềm năng hydrocarbon nước sâu và nước siêu sâu của Việt Nam, hiện trạng và những thách thức, đồng thời đề xuất các bước cần thiết để có thể giúp Việt Nam khai thác nguồn tài nguyên hydrocacbon khổng lồ chưa được khám phá này.

Từ khoá: Khoan nước sâu, sự tiến bộ trong thi công khoan và thiết kế giếng, khoan nước sâu ở Việt Nam, thực trạng khoan nước sâu ở Việt Nam, thách thức cho Việt Nam, bài học cho Việt Nam

[1]*Khoa Kỹ Thuật Địa Chất Và Dầu Khí, Đại học Bách Khoa thành phố Hồ Chí Minh (HCMUT), 268 đường Lý Thường Kiệt, Quận 10, Thành phố Hồ Chí Minh, Việt Nam.*

[2]*Đại Học Quốc Gia Thành Phố Hồ Chí Minh, Phường Linh Trung, Thành Phố Thủ Đức, Việt Nam*

[3]*Văn phòng đào tạo quốc tế, Đại Học Bách Khoa thành phố Hồ Chí Minh, 268 đường Lý Thường Kiệt, Quận 10, Thành phố Hồ Chí Minh, Việt Nam.*

Liên hệ

Trần Trung Dũng, Khoa Kỹ Thuật Địa Chất Và Dầu Khí, Đại học Bách Khoa thành phố Hồ Chí Minh (HCMUT), 268 đường Lý Thường Kiệt, Quận 10, Thành phố Hồ Chí Minh, Việt Nam.

Đại Học Quốc Gia Thành Phố Hồ Chí Minh, Phường Linh Trung, Thành Phố Thủ Đức, Việt Nam

Email: dungtt@hcmut.edu.vn

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