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Geosteering in deep water wells: A theoretical review of challenges and solutions

Femi Bamidele Onita [1,]* and Obinna Joshua Ochulor [2]

[1] *Shell Deep water, Gulf of Mexico, USA.*

[2] *Sheval Engineering Services Limited, Nigeria.*

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Abstract

Geosteering in deep water wells presents unique challenges and opportunities within the oil and gas industry. This paper comprehensively reviews these challenges, including geological uncertainties, technological limitations, operational constraints, and economic and safety risks. Advanced geosteering tools and techniques, such as : Real time borehole image, resistivity inversion, anisotropy measurements, are discussed alongside the integration and the application of machine learning (ML) and artificial intelligence (AI) to enhance decision-making processes. Predictive modeling and uncertainty quantification are explored as essential components for optimizing wellbore placement and managing risks. Furthermore, the paper highlights emerging trends in geosteering technology, including augmented reality (AR), virtual reality (VR), and high-resolution sensors, which promise to improve the accuracy and efficiency of drilling operations. Sustainability considerations are also addressed, emphasizing the need for environmentally friendly drilling practices and reducing the industry's environmental footprint. This theoretical review underscores the importance of continuous technological advancements and the adoption of best practices to overcome the complexities of deepwater drilling. By leveraging innovative solutions and prioritizing sustainability, the oil and gas industry can enhance the success and safety of drilling operations, ensuring long-term viability and environmental stewardship.

Keywords: Geosteering; Deep Water Wells; Machine Learning; Predictive Modeling; Sustainability

1 Introduction

1.1 Overview of Geosteering

Geosteering, a portmanteau of "geology" and "steering," is a technology-driven method used in the oil and gas industry to guide the drilling of wells. Unlike traditional drilling techniques, which follow a predetermined, straight-line path, geosteering allows for dynamic adjustments to the drill bit's direction based on real-time data. This process involves integrating geological and petrophysical data to make informed decisions about the well's trajectory, ensuring it stays within the desired reservoir zone (Babayeju, Jambol, & Esiri, 2024). The primary objective of geosteering is to maximize hydrocarbon recovery by accurately navigating the drill bit through the most productive parts of the reservoir. This technique is especially valuable in complex geological settings, where the precise placement of the wellbore can significantly impact the efficiency and success of extraction operations (Ojeh-Oziegbe et al., 2024).

Geosteering has become a cornerstone in modern oil and gas extraction because it enhances well placement accuracy and improves reservoir contact. By continuously analyzing data from logging-while-drilling (LWD) and measurement-while-drilling (MWD) tools, geosteering professionals can make real-time adjustments to the drilling direction. This capability reduces the risk of drilling dry holes or missing the target reservoir altogether. Furthermore, geosteering optimizes wellbore placement to ensure that the well intersects the reservoir at the most productive angle, enhancing the overall recovery factor and extending the reservoir's life. The advent of geosteering has revolutionized the oil and

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* Corresponding author: Femi Bamidele Onita

gas industry, making it possible to extract hydrocarbons more efficiently and economically (Ellis & Singer, 2007; Waltenberger, 2023).

1.2 Significance in Deep Water Wells

Geosteering is particularly crucial in deep water wells, where the challenges and risks associated with drilling are significantly amplified. Deep water drilling involves accessing hydrocarbon reserves located beneath the ocean floor, often at depths of several thousand meters. The geological formations in these environments are typically more complex and less well-understood than onshore or shallow water settings (Schofield, Lewis, Smedley, Bloomfield, & Boon, 2014). Consequently, the margin for error in well placement is exceptionally narrow. A slight deviation from the planned well path can lead to drilling into non-productive zones or even result in catastrophic wellbore instability and blowouts. In such high-stakes scenarios, the precision and adaptability provided by geosteering are indispensable.

One of the primary challenges in deep water drilling is the limited availability of real-time geological data. Unlike onshore drilling, where seismic surveys and other geophysical methods can provide detailed subsurface images, deep water environments often lack comprehensive pre-drill data. This makes it difficult to predict the exact location and extent of the reservoir. Geosteering mitigates this challenge by utilizing LWD and MWD tools that provide continuous real-time feedback on the geological conditions encountered during drilling. By interpreting this data on the fly, geosteering experts can adjust the well trajectory to stay within the optimal reservoir zone, even without extensive pre-drill information. This real-time adaptability is vital for the success of deep water drilling operations (Luthi, 2001; Waltenberger, 2023).

Moreover, deep water wells are typically more expensive to drill and complete than their onshore counterparts. The need for specialized equipment drives the costs associated with deep water drilling, the logistical complexities of operating in remote offshore locations, and the increased safety measures required to protect personnel and the environment. Given these high costs, maximizing the chances of drilling successful wells is imperative. Geosteering is critical in minimizing the risk of drilling dry holes and optimizing well placement to enhance hydrocarbon recovery. The economic benefits of successful geosteering in deep water wells can be substantial, making it a key enabler of cost-effective deep water oil and gas production (Aird, 2018; Saikia & Shanker, 2019).

1.3 Objectives of the Paper

The primary objective of this paper is to provide a comprehensive theoretical review of the challenges and solutions associated with geosteering in deep water wells. By examining the technical, operational, and economic aspects of geosteering, this paper aims to shed light on the factors that influence the success of geosteering operations in deep water environments. In doing so, it seeks to identify the key challenges geosteering professionals face and explore the latest technological advancements and methodologies developed to overcome them.

This paper will begin by detailing the challenges encountered in geosteering deep water wells, including geological uncertainties, technological limitations, operational constraints, and economic and safety risks. It will then review the solutions and technological advances that have been implemented to address these challenges, focusing on advanced geosteering tools, real-time data integration, machine learning and artificial intelligence applications, and enhanced drilling techniques. Additionally, the paper will explore theoretical models and approaches used in geosteering, such as predictive modeling, uncertainty quantification, and decision-making frameworks.

Ultimately, this paper aims to thoroughly understand geosteering in deep water wells and highlight the emerging trends and future directions in this field. By offering insights into the theoretical and practical aspects of geosteering, this paper hopes to contribute to the ongoing efforts to improve deep water oil and gas extraction's efficiency, safety, and economic viability.

2 Challenges in Geosteering Deep Water Wells

2.1 Geological Uncertainties

Geosteering in deep water wells presents numerous challenges, primarily due to the complexities of subsurface geology. The geological formations encountered in deep water environments are often intricate and less predictable than those onshore or shallow water. These formations can include various layers of sediment, rock, and potential hydrocarbon reservoirs shaped by millions of years of geological processes. The heterogeneity of these formations adds a layer of uncertainty to geosteering operations. For instance, the presence of faults, fractures, and varying lithologies can significantly impact the wellbore's path and the drilling operation's overall success (Wang, 2017).

The lack of comprehensive geological data further exacerbates these uncertainties. Deep water drilling operations typically rely on seismic surveys and other geophysical methods to provide an initial understanding of the subsurface. However, the resolution and accuracy of these surveys can be limited, leading to gaps in the geological model. As a result, real-time data obtained during drilling becomes crucial for making informed decisions. The dynamic nature of deep water environments means that geological conditions can change rapidly, requiring continuous adjustments to the well trajectory. This need for adaptability underscores the importance of advanced geosteering techniques and real-time data interpretation (Onajite, 2021).

2.2 Technological Limitations

Technological limitations pose significant constraints on geosteering in deep water wells. The tools and equipment used in geosteering must operate reliably under extreme conditions, including high pressures and temperatures. Measurement-while-drilling (MWD) and logging-while-drilling (LWD) tools, which provide real-time data on the subsurface geology, are critical for successful geosteering. However, these tools can be prone to malfunctions and inaccuracies, particularly in harsh deep water environments. The reliability of these tools is paramount, as any failure can lead to incorrect decisions and potentially catastrophic consequences (Modarres & Groth, 2023).

Data acquisition is another technological challenge. The depth and environmental conditions of deep water wells often hinder real-time data transmission from the wellbore to the surface. Delays or disruptions in data transmission can impede the ability of geosteering professionals to make timely adjustments to the drilling direction (Bartosik & Amirlatifi, 2020). Additionally, the resolution of the data collected can be insufficient for detailed geological interpretation, necessitating sophisticated data processing and interpretation techniques. Advanced algorithms and machine learning models are increasingly being employed to enhance the accuracy and reliability of geosteering data. However, these technologies are still evolving and may not always provide the desired level of precision (Gupta et al., 2020).

2.3 Operational Constraints

Operational constraints in geosteering deep water wells are multifaceted, involving challenges related to drilling accuracy, environmental conditions, and logistical complexities. Drilling accuracy is critical for ensuring the wellbore remains within the target reservoir zone. However, maintaining precise control over the drill bit's direction is difficult in deep water environments due to high pressures, varying rock hardness, and unpredictable geological features. The need for precise wellbore placement demands constant monitoring and real-time adjustments, increasing the complexity of the drilling operation (Damski & El Afifi, 2021).

Environmental conditions in deep water settings can also pose significant challenges. Harsh weather, strong ocean currents, and deep-sea pressures create a demanding operational environment. These conditions can affect the drilling rig's stability, the wellbore's integrity, and the drilling equipment's performance. Ensuring the safety and reliability of operations under such conditions requires robust engineering solutions and contingency planning (Danovaro et al., 2020; Esiri, Babayeju, & Ekemezie, 2024a).

Logistical complexities further compound the operational constraints. Deep water drilling operations are typically conducted far from shore, necessitating extensive planning and coordination for transporting equipment, personnel, and supplies. The remoteness of these operations also means that any technical issues or emergencies can be more complex and time-consuming to address. Effective communication and coordination among the various teams involved in the drilling operation are essential for overcoming these logistical challenges (Zhdaneev, Frolov, & Petrakov, 2021).

2.4 Economic and Safety Risks

The economic and safety risks of geosteering in deep water wells are considerable. The high costs of deep water drilling stem from the need for specialized equipment, the complexity of the operations, and the extended timelines often required to complete these projects. The financial stakes are high, as any failure or inefficiency can lead to substantial economic losses. Drilling dry holes or missing the target reservoir can result in wasted resources and lost investment. Therefore, optimizing the success rate of drilling operations through effective geosteering is of paramount importance for the economic viability of deep water projects.

Safety risks are equally significant. The extreme conditions of deep water drilling present inherent hazards to personnel and the environment. High pressures and temperatures can compromise the integrity of the wellbore, increasing the risk of blowouts and other catastrophic events. The environmental impact of such incidents can be severe, with potential oil spills causing long-term damage to marine ecosystems. Ensuring the safety of operations requires stringent adherence to safety protocols, regular equipment maintenance, and continuous monitoring of well conditions. Implementing advanced geosteering techniques can help mitigate some risks by improving drilling accuracy and reducing the likelihood of encountering hazardous situations (Babayeju et al., 2024; Mele et al., 2022).

3 Solutions and Advances in Technology

3.1 Advanced Geosteering Tools

The evolution of geosteering tools and equipment has significantly enhanced the ability to navigate complex geological formations in deep water wells. Modern geosteering relies heavily on advanced Measurement-While-Drilling and Logging-While-Drilling tools. These tools provide real-time data on the geological and petrophysical properties of the formations encountered by the drill bit. MWD tools measure parameters such as azimuth, inclination, and tool face orientation, while LWD tools provide detailed information on formation properties, including resistivity, density, porosity, and gamma-ray measurements. Together, these tools allow for precise control over the drilling direction and ensure that the wellbore stays within the optimal reservoir zone (Sinha et al., 2021).

Recent advancements have improved these tools' resolution, accuracy, and reliability. For example, high-resolution resistivity tools can detect fine-scale geological features that were previously difficult to identify, such as thin bed boundaries and fractures. Additionally, multi-component LWD tools now offer enhanced imaging capabilities, allowing for a more detailed and comprehensive understanding of the subsurface. These improvements enable geosteering professionals to make more informed decisions and adjust the drilling trajectory with greater confidence, ultimately increasing the success rate of deep water drilling operations (Horstmann et al., 2020).

3.2 Real-Time Data Integration

The integration of real-time data is critical for effective decision-making in geosteering. As drilling progresses, MWD and LWD tools continuously transmit data to the surface, where it is processed and analyzed by geosteering experts. This real-time data provides valuable insights into the subsurface conditions, allowing for immediate adjustments to the drilling direction. Making these adjustments on the fly is essential for navigating complex geological formations and avoiding non-productive zones.

Recent technological advancements have significantly enhanced the capability to integrate and interpret real-time data. Advanced data processing algorithms and software platforms enable seamless data integration from multiple sources, providing a comprehensive and coherent picture of the subsurface. For instance, real-time data from MWD and LWD tools can be combined with pre-drill seismic data and geological models to create a dynamic and updated representation of the subsurface. This integrated approach allows geosteering professionals to identify trends, detect anomalies, and predict the behavior of geological formations with greater accuracy.

Furthermore, cloud-based platforms have revolutionized data integration and collaboration in geosteering. These platforms enable real-time data sharing and collaboration among geographically dispersed teams, allowing faster and more coordinated decision-making. By leveraging cloud technology, geosteering experts can access and analyze data from anywhere worldwide, ensuring that the most knowledgeable and experienced personnel are involved in critical decision-making processes. This level of connectivity and collaboration enhances the overall efficiency and effectiveness of geosteering operations (Al-Rbeawi, 2023; Waltenberger, 2023).

3.3 Machine Learning and AI Applications

Applying machine learning and artificial intelligence has brought a new dimension to geosteering, offering significant improvements in accuracy and efficiency. Machine learning algorithms can analyze vast amounts of data and identify patterns and correlations that may not be apparent to human analysts. In geosteering, these algorithms can predict geological features, optimize wellbore placement, and enhance real-time decision-making.

One of the key applications of ML in geosteering is predictive modeling. Machine learning models can be trained on historical drilling data to predict the behavior of geological formations and the response of the drilling equipment. These models can then be used to guide the drilling process, reducing the uncertainty and improving the accuracy of wellbore placement. Additionally, AI-driven analytics can continuously monitor real-time data, detect anomalies, and provide actionable insights to geosteering professionals. This capability allows for proactive adjustments to the drilling trajectory, minimizing the risk of drilling into non-productive zones or encountering hazardous conditions (Ogbu, Ozowe, & Ikevuje, 2024; Ozowe, Daramola, & Ekemezie, 2024b).

AI is also being used to automate and optimize various aspects of the geosteering process. For example, AI algorithms can automate the interpretation of LWD data, reducing the workload of geosteering experts and allowing them to focus on more complex and strategic decision-making tasks. Furthermore, AI-driven optimization techniques can design optimal drilling trajectories, considering reservoir geometry, rock properties, and drilling constraints. These advancements in ML and AI are transforming geosteering into a more data-driven and efficient process, enhancing the overall success and cost-effectiveness of deep water drilling operations (Feng, 2024; Vithanage, Harrison, & DeSilva, 2019).

3.4 Enhanced Drilling Techniques

Innovations in drilling techniques are also playing a crucial role in improving geosteering outcomes. Directional drilling technologies have advanced significantly, allowing for greater precision and control over the drilling direction. Rotary steerable systems (RSS), for example, enable continuous steering of the drill bit without the need to stop and make manual adjustments. This capability ensures smoother and more accurate wellbore trajectories, reducing the risk of drilling deviations and increasing the efficiency of the drilling process.

Another significant advancement is the development of steerable drilling motors and adjustable stabilizers. These tools provide additional control over the drilling direction and allow for fine-tuning of the wellbore trajectory. By combining these advanced drilling technologies with real-time data from MWD and LWD tools, geosteering professionals can achieve higher accuracy and precision in wellbore placement (Esiri, Babayeju, & Ekemezie, 2024b; Ogbu, Iwe, Ozowe, & Ikevuje, 2024).

Enhanced drilling techniques also include advanced drilling fluids and wellbore stability technologies. Drilling fluids are critical in maintaining wellbore stability and preventing issues such as borehole collapse and stuck pipes. Advanced drilling fluids are designed to optimize wellbore stability, minimize formation damage, and enhance the overall drilling performance. Additionally, wellbore stability technologies, such as managed pressure drilling (MPD) and wellbore strengthening techniques, help to manage downhole pressures and prevent wellbore instability, further improving the success of geosteering operations (Kalhor Mohammadi, Riahi, & Boek, 2023).

4 Theoretical Models and Approaches

4.1 Predictive Modeling

Predictive modeling forms the cornerstone of theoretical approaches in geosteering, particularly in deep water wells where geological formations can be complex and unpredictable. These models utilize historical data and real-time inputs to forecast the subsurface conditions and behavior of geological formations. One of the primary tools in predictive modeling is using geological models that incorporate data from seismic surveys, well logs, core samples, and other geophysical data. These models help create a three-dimensional representation of the subsurface, which is essential for planning and guiding the wellbore trajectory.

Geological models are complemented by petrophysical models, which provide detailed information about the reservoir's rock properties and fluid content. Petrophysical models are built using data from logging-while-drilling and measurement-while-drilling tools, which offer continuous measurements of properties such as porosity, permeability, and fluid saturation. By integrating geological and petrophysical models, geosteering professionals can predict the location and extent of hydrocarbon-bearing formations and adjust the drilling path to maximize reservoir contact (Bär, Reinsch, & Bott, 2020; Radwan, 2022).

In addition to static models, dynamic predictive models are used to simulate the behavior of geological formations under various drilling scenarios. These models incorporate pressure changes, fluid flow, and rock mechanics to predict how the formation will respond to drilling operations. For instance, reservoir simulation models can forecast the movement of hydrocarbons within the reservoir over time, helping to optimize well placement and production strategies. Using these predictive models, geosteering experts can anticipate potential challenges and make proactive decisions to mitigate risks and improve drilling outcomes (Sarker, 2021; Zhdaneev et al., 2021).

4.2 Uncertainty Quantification

Uncertainty quantification is critical to geosteering, as it addresses the inherent uncertainties in geological data and modeling. Quantifying and managing uncertainty is essential for making informed decisions and minimizing risks in deep water drilling operations. Various methods and approaches are employed to quantify uncertainty in geosteering, ranging from statistical techniques to probabilistic modeling.

One standard method for uncertainty quantification is the use of Monte Carlo simulations. This technique generates many random samples from the input data to distribute possible outcomes. By running multiple simulations, geosteering professionals can assess the range of potential scenarios and their associated probabilities. Monte Carlo simulations help identify the most likely outcomes and the confidence level in the predictions, providing a robust basis for decision-making (Fong, Li, Dey, Crespo, & Herrera-Viedma, 2020).

Another approach to uncertainty quantification is using Bayesian inference, which combines prior knowledge with new data to update the probability estimates of different geological scenarios. Bayesian methods are instrumental in geosteering because they allow for the incorporation of real-time data and continuous learning from the drilling process. As new data is acquired from MWD and LWD tools, the Bayesian model updates its predictions and reduces uncertainty, leading to more accurate and reliable decision-making (Isheyskiy & Sanchidrián, 2020; Ozowe, Daramola, & Ekemezie, 2024a).

Geostatistical methods are also employed to quantify spatial uncertainty in geological models. Techniques such as kriging and stochastic modeling are used to create multiple realizations of the subsurface, each representing a different possible configuration of geological features. These realizations provide a range of potential scenarios, helping geosteering professionals to understand the variability and uncertainty in the subsurface geology. By analyzing these scenarios, they can identify areas of high uncertainty and focus on obtaining additional data to reduce these uncertainties (Azevedo, Paneiro, Santos, & Soares, 2020).

4.3 Decision-Making Frameworks

The decision-making process in geosteering is guided by theoretical frameworks that integrate predictive modeling and uncertainty quantification to optimize well placement and maximize hydrocarbon recovery. These frameworks provide a structured approach to evaluating different drilling scenarios and selecting the best action based on the available data and model predictions.

One of the key decision-making frameworks in geosteering is the value of information (VOI) analysis. VOI analysis assesses the potential benefits of acquiring additional data before deciding. By quantifying the value of new information, the subsurface team can determine whether the potential improvement in decision quality justifies the cost and effort of obtaining the data. VOI analysis is instrumental in deep water drilling, where the cost of data acquisition can be high, and it helps to prioritize data collection efforts and allocate resources effectively (Vilela, Oluyemi, & Petrovski, 2020).

Another essential framework is decision tree analysis, which maps out the different possible outcomes of a drilling decision and the associated probabilities and costs. Decision trees visually represent the decision process, allowing subsurface team to evaluate the trade-offs between different options and select the one that maximizes the expected value. By incorporating uncertainty quantification and predictive modeling into the decision tree, they can account for the various risks and uncertainties involved in the drilling operation (Osarogiagbon, Khan, Venkatesan, & Gillard, 2021).

Risk assessment and management frameworks are also essential for guiding decision-making in geosteering. These frameworks involve identifying potential risks, evaluating their impact and likelihood, and implementing mitigation strategies to minimize adverse outcomes. In deep water drilling, risk management is critical due to the high stakes and potential consequences of drilling failures. By systematically assessing risks and developing contingency plans, the subsurface team can enhance the safety and reliability of their operations (Muhammad, Cheraghi, Alyaev, Srivastava, & Bratvold, 2024).

Moreover, integrating real-time data and adaptive decision-making frameworks has become increasingly crucial in geosteering. Adaptive frameworks allow for continuous monitoring and adjustment of the drilling strategy based on real-time data and evolving conditions. This dynamic approach enables geosteering professionals to respond quickly to unexpected changes in the subsurface and optimize the drilling trajectory in real time. Adaptive decision-making frameworks leverage advanced data analytics and machine learning algorithms to continuously update the predictive models and improve the accuracy and reliability of the decisions (Gooneratne et al., 2020).

5 Future Directions

5.1 Emerging Trends

Geosteering technology and practices are on the cusp of significant advancements driven by emerging trends. One of the most promising trends is the increased use of artificial intelligence and machine learning (ML) to enhance real-time data interpretation and decision-making processes. AI algorithms can analyze vast amounts of data more efficiently than human analysts, identifying patterns and making predictions that improve wellbore placement and drilling accuracy. This capability is particularly beneficial in complex deep water environments with less predictable geological formations.

Another trend is integrating augmented reality and virtual reality technologies. These tools provide the subsurface team with immersive, three-dimensional visualizations of the subsurface, enhancing their ability to interpret data and make informed decisions. AR and VR can simulate drilling scenarios, allowing for better planning and risk assessment. Additionally, advancements in sensor technology and data acquisition tools are expected to continue. High-resolution sensors that provide more detailed geological information will improve the accuracy of geosteering operations. Furthermore, developing autonomous drilling systems that use advanced robotics and AI to control the drilling process holds promise for increasing efficiency and safety in deep water drilling.

5.2 Long-term Sustainability

As the oil and gas industry moves towards more sustainable practices, future developments in drilling technology must address environmental concerns. One key area is the reduction of the environmental footprint of drilling operations. Enhanced precision in wellbore placement can minimize the number of wells needed to access a reservoir, thereby reducing surface disruption and environmental impact.

Using environmentally friendly drilling fluids and wellbore stability technologies is another important aspect. These innovations can mitigate the risk of spills and contamination, protecting marine ecosystems. Additionally, as regulatory frameworks become more stringent, the industry will need to adopt best practices for environmental stewardship, including using low-impact drilling techniques and implementing comprehensive environmental monitoring programs.

The push towards digitalization and adoption of remote monitoring and control systems also contribute to sustainability. By enabling real-time monitoring and remote operation of drilling rigs, these technologies reduce the need for personnel to be physically present on-site, lowering the carbon footprint associated with transportation and logistics.

6 Conclusion

Geosteering in deep water wells presents many challenges, including geological uncertainties, technological limitations, operational constraints, and economic and safety risks. Addressing these challenges requires integrating advanced geosteering tools, real-time data interpretation, machine learning and AI applications, and enhanced drilling techniques. Predictive modeling and uncertainty quantification are essential for making informed decisions and optimizing wellbore placement.

The future of geosteering lies in adopting emerging technologies such as AI, ML, AR, VR, and advanced sensors. These technologies will enhance the precision and efficiency of geosteering operations, allowing for better navigation of complex geological formations and improved hydrocarbon recovery. Furthermore, sustainability considerations are becoming increasingly important, and future developments must focus on minimizing the environmental impact of drilling operations and adopting more eco-friendly practices. In conclusion, the continuous evolution of geosteering technology and practices is crucial for overcoming the challenges of deep water drilling and ensuring the long-term sustainability of the oil and gas industry. By embracing emerging trends and prioritizing environmental stewardship, the industry can achieve more efficient, safe, and sustainable geosteering operations in the future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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