

Optimizing Geological Well Design for Deep Shale Gas Wells in the Southern Sichuan Basin

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Abstract:

Deep shale gas is currently recognized as a highly productive play within the Sichuan Basin, highlighting the significance of its exploration and exploitation. However, the complex geological conditions of deep shale gas in the southern area of the Sichuan Basin presents significant challenges to achieving safe, high-quality and rapid drilling. This article focuses on optimizing geological well design to improve deep shale gas drilling performance by analyzing key components of its geological conditions, such as stratigraphic prediction, well trajectory control, accurate reservoir targeting, pressure forecasting, and risk identification. The proposed methodology aims to offer a more precise and efficient approach to deep shale gas well design and has been successfully implemented in the Sichuan oilfield.

Keywords:

Deep Shale Gas, Geological Well Design, Stratigraphic Prediction, Trajectory Control; Reservoir Targeting, Pressure Prediction, Risk Identification

1. Introduction

Geological Well design is a multidisciplinary effort that integrates various technical and operational aspects to achieve a successful drilling project. It is crucial for ensuring drilling safety, minimizes risks to both personnel and the environment, and maximizes the well's production potential while reducing drilling costs and time. Accurate well design is fundamental, defining the well-bore's exact location and inclination to achieve efficient intersection with the intended reservoir[1]. With the exploration and development of shale gas in southern Sichuan moving into deep layers, the geological well design is facing greater risks and challenges. Therefore, reevaluate the critical aspects of well design is essential for the success, safety, and efficiency of drilling operations. An optimized well design can accurately target the reservoir, reduce risks to personnel and equipment, enhance drilling efficiency, and significantly elevate the rate of production.

2. Geological Setting

The study area is located in the southern part of the Sichuan Basin, which mainly includes the area west of the Qiyueshan fault zone and the area to the east of the Huayingshan fault. It is a low-fold structural belt in southern Sichuan, positioned between the southern flank of the paleo-uplift and the southeastern Sichuan fold belt (Figure 1).

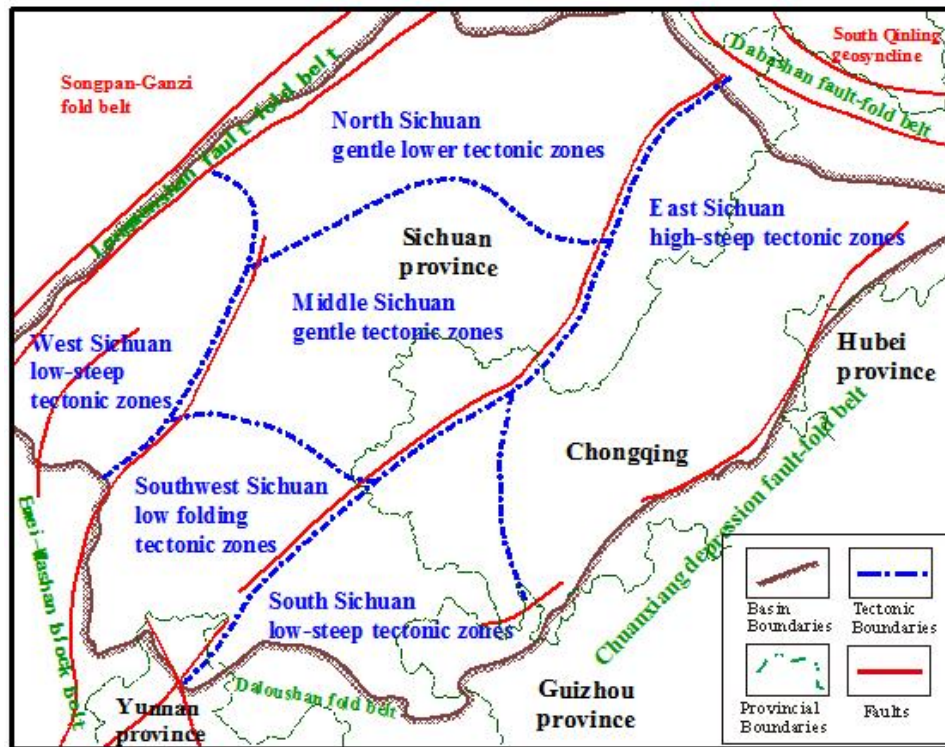


Figure 1. Sichuan Basin tectonic element sketch map.

The Sichuan Basin is located in the Upper Yangtze Platform and is classified as a craton basin. Prior to the Upper Triassic period, the basin was predominantly characterized by the stable sedimentary environment typical of a craton basin, with marine sedimentation being the primary depositional process. Exceptions to this were localized ancient uplifts, such as the Leshan Longnusi Uplift located to the north of the basin. However, influenced by the tectonic forces resulting from the collision and compression between the Indian Plate and the Eurasian Plate, along with the escape stress from the Indosinian subplate, the region began to experience significant tectonic activity around the Upper Triassic period. This led to the transformation of the basin's margins into folded mountains, and the basin itself shifted to a terrestrial sedimentary regime.

The faulting in the area is predominantly attributed to the large-scale compressional orogenic events that occurred during the Himalayan period. This tectonic phase was marked by the development of reverse faults, which continue to influence the structural and sedimentary characteristics of the Sichuan Basin. The evolution of the basin from a site of marine sedimentation to one of terrestrial deposition and the formation of its complex fault network are key elements in understanding the geological history and current dynamics of this region [2-12].

Vertically, the plastic mudstone layer of the Silurian Longmaxi acts as a regulatory zone, delineating two distinct sets of fault systems. These fault systems share

significant similarities in terms of strike, dip, and magnitude, reflecting their common genetic origins in controlling the primary structural morphology. However, the episodic tectonic movements during the Himalayan period have also led to the development of some faults within the upper fault system that lack genetic inheritance and similarity to the lower system. In terms of planar fault distribution, the principal faults that dictate the structural form predominantly exhibit a northeasterly orientation, influenced by the combined effects of two directional forces. Additionally, the southern compressional forces encountering the resistance of the northern ancient uplift have led to a gradual stress release through shear movements from south to north. This process has facilitated the emergence of a series of nearly east-west oriented faults within the block, which intersect the main faults at a noticeable angle. This complex interplay of forces has contributed to the intricate fault network observed in the region.

3. Design Challenges in Deep Shale Gas Wells

3.1. Structures and developed fault systems

The study area, situated within the southern Sichuan Basin, is marked by pronounced fold deformation. The deformation is particularly intense in the northeastern part, gradually easing towards the southwest, where it forms narrow and steep anticlines as well as broad and gentle synclines. This regional structural pattern is predominantly influenced by the Huaying Mountain Fault, the Qijiang Fault, and the primary faults within the Qiyue Mountain Fault Zone. The overarching geological structure is characterized by expansive, gentle synclines and low, steep slopes, which collectively encompass an area more than 20 times larger than that of the anticline structures [13]. Significant faults are prominently developed along the flanks of the main structural framework, exerting a decisive influence on the overall structural configuration. The area is further distinguished by a multi-stage and multi-scale distribution of faults. Commencing from the Wufeng Formation and extending upwards, these faults exhibit a pattern of development and inheritance, indicating a complex interplay of tectonic forces throughout geological time.

3.2. Thickness of overlying strata

Drilling data and observations from adjacent surface outcrops reveal that in the study area, the Silurian strata were deposited continuously on top of the shale from the Ordovician Wufeng Formation. Influenced by the Caledonian Orogeny and the uplift of the Leshan Longnvsi ancient uplift, the Silurian formations experienced varying degrees of erosion. This has resulted in the Longmaxi Formation being in contact with a variety of different overlying strata.

The strata predominantly exposed at the surface in the region are from the Middle Jurassic Shaximiao Formation, with some areas also revealing Triassic formations. Notably, within the Triassic strata above the study area, a gypsum layer is present. The Shaximiao Formation, Lianggaoshan Formation, Ziliujing Formation, Xujiache Formation, Feixianguan Formation, Longtan Formation, Liangshan Formation, Hanjiadian Formation, and Shiniulan Formation all contain substantial mudstone layers.

The thickness of the Maokou Formation is significantly influenced by the Dongwu Movement, being thinnest in the central area of the Luzhou ancient uplift and increasing in thickness towards the periphery of this uplift. The lithology of the

overlying strata within the study area exhibits considerable variability, with notable horizontal changes in thickness. These geological complexities pose challenges for the accurate prediction of stratigraphic depths in drilling geological design.

3.3. Multiple vertical gas bearing layers

The strata of the Sichuan Basin have experienced a significant shift from marine to continental sedimentation, largely driven by a series of tectonic movements. These include the Caledonian, Hercynian, Indosinian, Yanshan, and Himalayan orogenies, which have collectively shaped the basin's intricate structural deformation and sedimentary environments [13]. The study area is notable for its numerous reservoir and gas-bearing strata, encompassing 13 industrial production layers and a single oil-bearing layer. The complexity of the vertical pressure system within the basin presents considerable challenges for accurate prediction and modeling.

3.4. Difference of formation pressure in overlying strata

Decades of exploration and development in the southern Sichuan region have yielded significant findings, particularly in the Xujiahe, Jialingjiang, Changxing, and Maokou formations. The gas reservoirs of the Lower Permian are primarily of the porous fractured and fracture karst types. Their distribution is governed by the development of fracture systems, resulting in an unstable distribution both vertically and horizontally. The pressure coefficient of these reservoirs is closely tied to the specific fracture systems they inhabit, leading to considerable variations in pressure even within the same drilling area.

Reservoirs in the Jiasi to Jiasan sections are mainly associated with ancient karst fractures and caves, largely concentrated around the core and its extensions of the Luzhou ancient uplift. Structural factors prevent the presence of an effective gypsum rock layer as a cap rock in these areas. The Jialingjiang Formation initially exhibits atmospheric pressure in the central uplift, contrasted by high-pressure systems to the north and south.

The lateral variation in formation pressure within the overlying strata is marked, and the pressure coefficient of the gas reservoirs has decreased over years of extraction, leading to the creation of goaf. This scenario makes the prediction of formation pressure a complex task in the geological design of deep shale gas wells in the southern Sichuan region.

3.5. Geological risk prediction

The Sichuan Basin is notable for having the highest number and reserves of hydrogen sulfide gas reservoirs discovered in China. It features multiple layers that contain hydrogen sulfide, spanning from the Sinian to the Triassic periods. There is a notable variation in hydrogen sulfide content across different formations: the Triassic Feixianguan Formation has the highest concentration, with the Permian Changxing and Leikoupo formations following. The Permian Maokou Formation has comparatively lower hydrogen sulfide levels, while the Sinian Dengying Formation and Carboniferous Huanglong Formation exhibit more consistent hydrogen sulfide levels.

In the southern Sichuan gas region, while there are many hydrogen sulfide gas reservoirs, the content is typically low, typically less than 1%, and often below 0.5%, except in the Weiyan gas field. The Dengying Formation in the Weiyan gas field is

an exception, with an average hydrogen sulfide content of 1.1%, peaking at 3.44%. Thus, the southern Sichuan gas region is mainly characterized by micro-hydrogen sulfide gas reservoirs [14]. The overlying production layer of the Longmaxi Formation in the southern Sichuan region, starting from the Xujiahe Formation, generally contains hydrogen sulfide. Some strata may not inherently contain sulfur, the potential for sulfur-containing gas to migrate through faults or fractures poses a risk. Therefore, comprehensive risk assessment from various angles is essential in the geological well design process.

4. Key Elements of Geological Well Design

4.1. Stratigraphic Prediction

Stratigraphic layering is generally based on the depth of seismic prediction marker layers. This is further refined by incorporating the actual drilling data of the region. The layers are systematically organized and segmented, adjusting for the variations in actual drilling thickness. This stratification is conducted in a chronological order, from the oldest to the most recent strata, based on the depth of the marker layers. In predicting stratigraphic stratification, it is essential to consider the structural position of the design well. Calculate the dip angle of the formation using both the structural map and seismic profile, and integrate this with the actual drilling data from adjacent wells to accurately restore the true thickness of the formation, and calculate the apparent thickness of each layer of the design well. For wells that cross faults, accurately determine the breakpoint depth from the seismic profile, predict the fault's extension layer using the structural reflection map, and predict the thickness of the upper and lower wall strata of the fault to ensure a comprehensive understanding of the stratigraphy.

Given the complexities of pronounced lithological variations and thickness inconsistencies in the superjacent strata, it is imperative to continuously optimize and upgrade the predictive techniques for stratigraphic stratification. This involves employing advanced analytical methods and incorporating comprehensive geological data to improve the accuracy and reliability of the stratigraphic predictions.

Firstly, To effectively address the challenges of strong deformation in underground structures, the development of fault systems, and the considerable variations in the thickness of overlying strata, it is imperative to undertake a meticulous “three verifications and one implementation” approach during the stratigraphic stratification design process. This involves a comprehensive verification and analysis of the seismic profile, seismic reflection structure map, and the actual drilling altitude data from adjacent wells. The objective is to pinpoint any data discrepancies, understand the underlying reasons for these differences, and thereby establish a solid data foundation that is crucial for accurate stratigraphic stratification.

Secondly, in response to the discrepancies in stratigraphic stratification standards for old wells in the area, a unified regional stratification standard has been established by integrating combined logging data, summarizing regional stratigraphic characteristics, and re-dividing the drilled strata. This approach supports the geological design of drilling stratigraphic stratification, ensuring consistency and reliability in the interpretation and application of stratigraphic standards. (Figure 2).

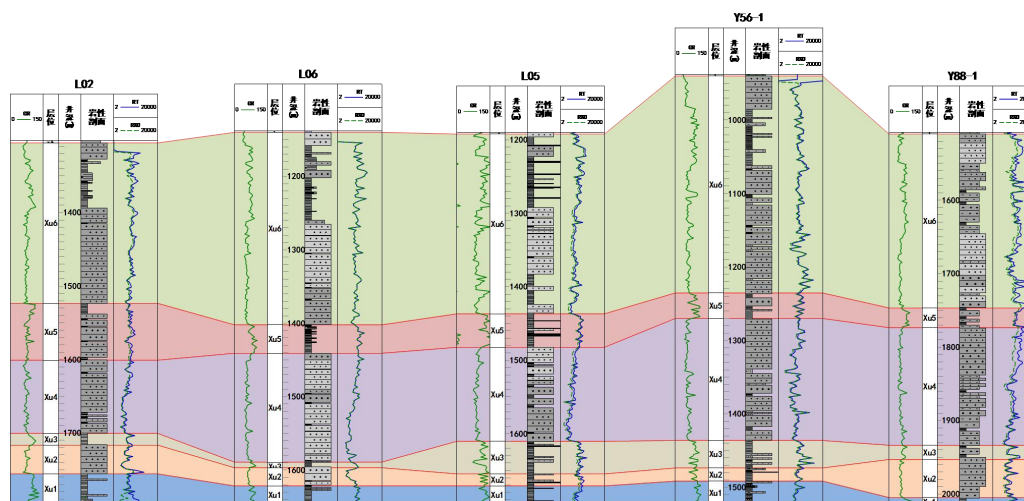


Figure 2. Comparison diagram of small layer division of Xujiahe Formation in southern Sichuan region.

Thirdly, based on actual drilling data and the consideration of structural evolution, research is conducted on the variations in strata thickness caused by erosion and sedimentation. Factors such as the development of unconformities, faults, changes in attitude, and different sedimentary systems significantly influence the distribution and thickness changes of strata. Identifying trends in strata erosion and areas of sedimentary thickness variation can effectively improve the accuracy depth and thickness measurements in stratigraphic analysis.

4.2. Trajectory Control

To address the complexities associated with the development of fault systems in the area, we employ a concept of “engineering geological integration”. This approach involves the predictive outcomes from multi-stage fault system analyses derived from seismic studies. We apply this integrated knowledge to forecast faults in the design of new wells, adhered to the “one well, one layer” methodology, guided by the engineering design trajectory. This method allows us to map the spatial distribution of fault systems, thereby accurately reflecting the depth of each stratum and the precise fault positions encountered during the drilling process. This comprehensive geological and engineering synthesis is crucial for the drilling geological design, ensuring that the wells are strategically positioned to navigate the intricate fault structures effectively (Figure 3).

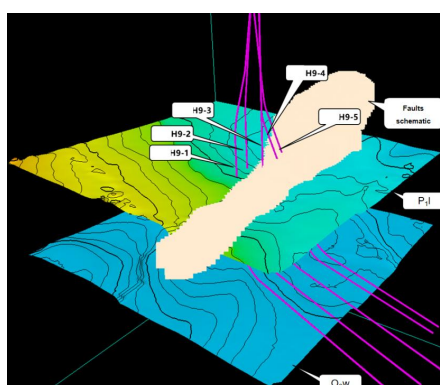


Figure 3. Platform well space schematic diagram.

4.3. Reservoir Targeting

The deep shale in the Wufeng Longmaxi Formation of the southern Sichuan region is characterized by a high organic matter content, with an average Total Organic Carbon (TOC) value of 3.37%, and is overmature, indicated by an average Reflectance of Organic Matter (RO) value of 2.24%. This formation also boasts a relatively high reservoir porosity, averaging 4.45%, and features a variety of pore types, including inorganic mineral and organic matter pores. Mineralogically, it is notable for its high quartz content (44.25%), low clay content (29.03%), and high brittle mineral content (57.35%), which, combined with good brittleness indices (55.35% for index I and 67.44% for index II), suggests favorable conditions for fracturing operations. Additionally, the shale reservoirs exhibit overpressure, with a pressure coefficient exceeding 2.0, and contain a substantial gas content ranging from 4.10 to 7.90 m³/t. These attributes collectively underscore the potential of the Wufeng Longmaxi Formation as a significant source of hydrocarbon resources in the southern Sichuan region [15].

Currently, the deep shale gas in southern Sichuan is in the midst of extensive development. To optimize the utilization of shale gas reservoirs and enhance the efficiency of development, horizontal wells are frequently employed in the deployment strategy. During the geological well design phase, it is customary to select wells with comparable structural positions, burial depths, and geological conditions as the design wells to serve as benchmarks. Utilizing the actual drilled reservoir data from these reference wells, we can accurately determine the target zones. This determination is further refined by integrating seismic profiles with structural data, which allows us to predict the precise depth at which these targets will be encountered. This integrated approach ensures a more precise and reliable prediction of the subsurface geology, facilitating more effective well design and drilling strategies.

Given the significant deformation of the underground structure in the study area, it is essential to refine the design of the horizontal well section once the extent of this section has been established. Utilizing seismic profiles, structural reflections, and other relevant data, we can anticipate variations in the dip angle of the formation's horizontal section. Additionally, by considering geological features such as anticlines and synclines, we can conduct a comprehensive analysis of potential minor deviations or faults that may occur during drilling.

This analysis provides essential insights for planning the trajectory of wells within the target formation. By delineating geological targets in both sectional and stratigraphic terms, we can achieve a precise characterization of the target body. This detailed understanding forms the basis for designing accurate horizontal well trajectories and serves as a guide for drilling operations.

Furthermore, this approach lays the groundwork for developing a well-guided plan, ensuring the optimal and efficient execution of drilling activities. It also sets the stage for achieving a high drilling rate within the geological target bodies, thereby enhancing the overall efficiency and effectiveness of the drilling process.

4.4. Pressure Prediction

Accurate prediction of formation pressure is crucial for ensuring the safety and efficiency of drilling operations. By integrating this data with the interpretation and processing of information from drilled wells, a more reliable forecast of the formation

pressure coefficient can be achieved. This comprehensive approach allows for a more precise estimation, which is essential for planning and executing drilling operations in a manner that minimizes risks and maximizes productivity.

In the southern Sichuan region, where challenges such as multiple vertical gas-bearing layers and pronounced variations in formation pressure distribution in the overlying strata are prevalent, a multi-step approach is essential.

Initially, during the early design phase, it is crucial to gather comprehensive regional data including drilling, testing, reservoir inversion, and karst exploration. This data aids in delineating the vertical profiles of normal pressure, high pressure, abnormally high pressure, and abnormally low pressure (goaf) layers within the design area. Subsequently, the structural positioning of the well must be taken into account, and seismic fine fracture characterization should be utilized to dynamically refine the geological understanding. Thirdly, collecting data on the development and production history of the well area is imperative. This information, along with the research findings on the distribution of karst fractures and caves in the overlying strata, facilitates an analysis of reservoir connectivity, potentially through the identification of fracture systems or structural traps. Fourthly, focusing on the underlying potential production layer, earthquake forward prediction should guide the prediction of potential development areas. Finally, a thorough analysis of the factors influencing formation pressure in the target layer is necessary, along with in-depth research into the prediction methods for the formation pressure coefficient.

The precise forecasting of formation pressure is pivotal for enhancing regional geological comprehension, ensuring well control safety, reducing drilling cycles, and broadening the scope of oil and gas discoveries.

4.5. Risk Identification

The technology for risk identification is a sophisticated approach that utilizes the analysis of actual conditions encountered during the drilling of nearby wells to inform well design [16]. This method allows for the anticipation of geological and operational challenges, enabling more precise planning and execution of drilling operations. By extrapolating from the data gathered in adjacent wells, such as geological formations, pressure profiles, and structural complexities, engineers can better prepare for and adapt to the unique conditions of each drilling site.

To enhance the safety and efficacy of deep shale gas well design in the southern Sichuan region, it is essential to develop a more sophisticated risk assessment system. Initially, well positioning need to be meticulously optimized, drawing on research findings to concentrate on the target strata and critical overlying layers. This involves conducting thorough structural interpretations and fault predictions to gain a detailed understanding of the geological complexities, including the distribution of fault lines. Additionally, potential faults that may be encountered during the drilling process should be analyzed to anticipate and mitigate risks. This includes providing early warnings for intervals that are susceptible to abnormally high pressures or loss of circulation, where there is a possibility that the predicted formation pressure coefficients could deviate from actual conditions. By integrating these predictive measures and risk assessments, the design of deep shale gas wells can be significantly improved, ensuring safer and more efficient drilling operations.

Secondly, a detailed analysis of pressure drop and reservoir connectivity in neighboring mining areas is crucial, coupled with vigilant monitoring for malignant

well leaks and pressure drop funnel layers that may be encountered during drilling operations. Moving forward, it is essential to gather inclination data from adjacent wells and actual drilling trajectories prior to drilling, emphasizing the need for heightened surveillance of wellbore trajectories and a keen observation of iron shavings in rock cuttings to preemptively avoid wellbore collisions. Subsequently, leveraging the gas analysis data from neighboring wells, a detailed distribution map of well locations with high hydrogen sulfide content in the southern Sichuan region will be crafted. This map will serve as a focal point for reminders, especially for wells identified with high hydrogen sulfide levels. Additionally, predictive assessments will be conducted for strata potentially harboring hydrogen sulfide, and a thorough analysis of fault distributions will be undertaken to evaluate the risk of sulfur-containing gases migrating upward through these faults. Ultimately, these measures will culminate in the provision of critical risk warnings, bolstering the overall preparedness and safety of drilling operations in the region.

Risk identification for complex drilling engineering scenarios is capable of issuing early alerts for potential complications that could arise during drilling operations. By analyzing these predictions, proactive and effective countermeasures can be devised to mitigate risks associated with various drilling challenges, including oil, gas, and water influxes, blowouts, wellbore leaks, and elevated casing pressures. This foresight enables drilling teams to implement strategic safety measures and operational adjustments, thereby enhancing the overall safety and success of the drilling project.

5. Conclusions

Effective well design requires accurate geological targeting to ensure the well-bore effectively intersects the desired reservoir. Structural integrity is paramount, with the well capable of withstanding subsurface pressures and external stresses. Safety measures are integral, safeguarding both personnel and the surrounding environment. Economic considerations drive the need for cost-effective solutions that yield optimal production with minimal downtime. Compliance with industry regulations and standards is non-negotiable, ensuring all activities are conducted responsibly. Moreover, well design should be adaptable, allowing for flexibility in the face of evolving technologies or reservoir conditions, and sustainable, minimizing environmental impact while supporting long-term production goals.

The optimization of deep shale gas well design, which is grounded in key factors such as layer prediction, reservoir targeting, pressure management, and risk identification, is crucial for enhancing the effectiveness, safety, and efficiency of drilling operations. By incorporating actual drilling results, this approach has been continuously refined through timely corrections, supplementation, and the summarization of experiences, culminating in a comprehensive methodology for the well design of deep shale gas. This methodology has been successfully implemented in the Sichuan oilfield, achieving a balance between technical precision, operational efficiency, and environmental stewardship.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Author Contributions

Conceptualization: Cao Wen, Wu Jiajie, He Jia; Methodology: Cao Wen, Wu Jiajie; Writing: Cao Wen, Hou Wanyi; Data collection: Gao Yu.

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