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論文題目	In-situ stress analysis and fracture characterization in oil reservoirs with complex geological settings: A multi-methodological approach in the Zagros fold and thrust belt 複雑な地質条件を有する石油貯留層における原位置応力とフラクチャーの総合解析：ザクロス褶曲衝上断層帯におけるマルチ手法の展開		

（論文内容の要旨）

Subduction of the Arabian tectonic plate under the Eurasian plate has controlled the geological evolution of the Zagros suture zone and is considered one of Earth's most prominent regions of convergent deformation. The study area represents a critical focal point for understanding tectonic processes and in-situ stress regimes due to its location along the Zagros suture zone. This zone is a key geological feature characterized by complex structural formations, active tectonic movements, and varied stress regimes. Complex structures with different stress regimes present challenges in tectonic studies and affect the effective production and development of hydrocarbon resources. Using a combination of conventional and image logs, this dissertation provides valuable insights into the tectonic and geomechanical characteristics of the Zagros suture zone. The study comprehensively analyzed stress magnitude and orientations, natural fractures, pore pressure, and stress regime in two oil fields located in the southwestern Zagros suture zone and one oil field in the northwestern Zagros suture zone. The main contents are described below.

Chapter Two focuses on the geology and tectonic background of the northwestern and southeastern part of the Zagros suture zone, specifically in the Kurdistan region of Iraq and the Dezful embayment southwest of Iran. It discusses how different tectonic forces have shaped the geology of the Zagros suture zone over various eras, with the current tectonic setting largely influenced by the collision of the Arabian and Eurasian plates. This chapter details the tectonic evolution of the Zagros suture zone, formed through various geological stages, and outlines the distinct geological structures and formations resulting from this evolution.

Chapter Three gave an overview of existing methods of determining and measuring in situ stress, classifying them into direct and indirect methods. This chapter explains that each stress measurement method has different merits and disadvantages and is applicable only under certain conditions. It discusses the reliability of different methods for this purpose, highlighting that breakout data from image logging can provide accurate stress orientations and magnitudes at intermediate depths. The chapter suggested that when combined with actual measurements from wellbore data, theoretical methods, such as the poroelastic strain model, can yield valuable insights about stress states in active tectonic regions.

Chapter Four investigated the present-day stress state of the northwestern section of the Zagros suture zone in the Kurdistan region of Iraq. In addition, it explains a comprehensive methodology for applying the breakout approach and poroelastic strain model to determine the orientation and magnitude of horizontal principal stresses. The stress pattern was determined by combining image logs and conventional logs. The results showed that the stress regime below the depth of 1600 m is thrust faulting, and above this depth, it transforms into a strike-slip fault regime. The mean azimuth of the maximum horizontal in-situ stress, N72°E, is consistent with the tectonic movement and previous studies in the nearby Zagros suture zone. Regarding drilling implications, the redistribution of stresses and the transition from a strike-slip faulting stress regime to a reverse fault stress regime are critical and will undoubtedly affect the stability of drilled wells throughout the field. The pattern of tectonic stress fields in northern Iraq was found to be mainly controlled by the collision between the Arabian and Eurasian plates.

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Chapter Five provides a detailed analysis of the stress state in the southeastern Zagros suture zone, underlining the complex interplay between thrust faulting and strike-slip regimes. The study comprehensively analyzed the magnitude and orientations of in situ stress, natural fractures, and pore pressure in two oil fields in the Zagros foothills. The findings of this study have significant implications for energy field development, optimizing drilling practices, wellbore stability, and reservoir management in similar geological settings. A total of 3.2 km length of images and conventional logs from seven wells in both fields were used to determine the magnitude and orientation of in situ stresses. The results revealed that the azimuth of maximum horizontal stress in Field A and Field B were N32°E and N55°E, respectively. Field A is located in the SW sector of Dezful embayment which is 60 Km away from the Field B in the NE sector of Dezful embayment. The orientation of natural fractures was found to be closely aligned with the maximum horizontal stresses, confirming the reliability of the stress analysis. Increasing differences between the azimuth of maximum horizontal stress based on breakout and drilling-induced tensile fractures with increasing depth indicated the complexities in the subsurface stress regime. The assessment of stress regimes highlighted its variations with depth. Field A transitioned from a distinct thrust faulting regime to a cross-over of thrust and strike-slip faulting regimes with increasing depth, whereas Field B maintained a consistent thrust faulting stress regime.

Chapter Six provides significant insights into the effectiveness of various supervised machine-learning classification models for identifying borehole breakouts by conventional logs. This chapter highlights the application of various supervised machine learning models, including K-Nearest Neighbors (KNN), Decision Tree (DT), Random Forest (RF), Support Vector Machine (SVM), and Extreme Gradient Boosting (XGBoost) for identifying borehole breakouts. With their ensemble approaches, the RF and XGBoost models demonstrated an accuracy of 92% and emerged as the most robust and accurate, maintaining high-performance metrics. In addition, this chapter provides a detailed examination of input parameters, revealing that combining all available well logs as input data improved the model's performance. Moreover, careful tuning of hyperparameters was vital in optimizing each model's ability to discern between breakout and non-breakout intervals effectively. The robustness evaluation process, employing a varying test data size and shuffle mode, has demonstrated the models' consistency and reliability, a testament to the robustness of the methodologies applied.

Chapter Seven sumrizes the conculusions of this dissertation.

In summary, this dissertation makes a substantial contribution to the field of structural geology and petroleum engineering by providing a comprehensive analysis of the tectonic and geomechanical dynamics of the Zagros suture zone. By integrating findings from various methodologies, including conventional and image logs, breakout analysis, and advanced machine learning techniques, this study offers a nuanced understanding of stress regimes, fracture patterns, and wellbore stability in key oil fields of this region. Such advancements would improve our understanding of the Zagros suture zone and provide valuable insights for energy field development, optimizing drilling practices, and reservoir management in similar geological settings, ultimately improving the efficiency and productivity of oil and gas operations in the region.

（続紙　２　）

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（論文審査の結果の要旨）

アラビアプレートとユーラシアプレートの境界に位置するザクロス褶曲衝上断層帯（略称ZFTB）は、複雑なプレート収束域の変形構造を有するとともに、世界的に豊富な石油資源を賦存している。この様な複雑な地質条件を有する地域では、既往研究が少ない原位置応力に関する研究が構造地質学、石油工学、岩盤工学などの分野で求められている。本論文では、ZFTB の北部と南部のそれぞれについて、石油坑井のイメージ検層データなどを用いて、当該地域の応力解析を行った。さらに、石油坑井の通常検層データに基づく坑壁安定性解析を可能にするために、機械学習（ML）によるボアホールブレイクアウト発生の有無を検出する手法の開発を行った。得られた成果は以下の 3 つに要約される。

(1) ZFTB の北部に位置するイラクの油田から、深度 2000 m 以上の坑井 2 本におけるイメージ検層データなどを用いて、ボアホールブレイクアウトによる応力解析を行った結果、最大水平主応力方向は北東–南西～東–西であることを示し、プレートの運動方向と概ね一致することを明らかにした。このことは、当地域の原位置応力がプレート衝突に支配されていることを示唆する。

(2) ZFTB の南部にあるイランの 2 つの油田において、最大深度約 4000 m の坑井 8 本のイメージ検層データよりボアホールブレイクアウトを抽出して応力解析を行った。その結果、最大水平主応力方向は ZFTB の北部とほぼ同様に、北東–南西になっていることを明らかにした。また、約 3400 m 以深の石油貯留層では、油水境界深度の付近で、原位置応力の状態が逆断層型から横ずれ断層型に変化しているという興味深い結果を得た。

(3) コストの高いイメージ検層データがない場合を想定して、通常の検層データを用いた機械学習によるボアホールブレイクアウト発生の有無を検出する手法を開発した。それにより、複数の通常検層データを用いた機械学習の適用によるボアホールブレイクアウトの検出結果の妥当性と本手法の有効性を示した。

以上、複雑な地質条件を有するザクロス褶曲衝上断層帯（ZFTB）北部および南部の油田における応力特性が解明され、当該地域のテクトニクスの理解や石油資源の効率的な開発に寄与する結果が得られただけでなく、機械学習による坑壁安定性の解析手法に関する新しい可能性が示された。本研究で得られた新知見は構造地質学分野での学術的な意義が大きく、かつ、石油工学分野での実用的価値があるため、本論文は、当該地球科学と地球工学の分野において、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和 6 年 2 月 15 日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。

要旨公開可能日：令和 6 年 6 月 24 日以降