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Study on crustal thickness and the prediction of prolific depressions: the Bohai Basin as an example

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Abstract
The deep crustal structure is closely related to oil and gas reserves. Predicting the oil and gas enrichment of depressions based on the Moho depth and crustal thickness is a promising research topic with significant implications for guiding exploration in petroliferous basins. In this study, seismic data were used as a constraint on the use of satellite gravity anomaly inversion to obtain the distribution of Moho depth and crustal thickness in the Bohai Basin. Stretching factors were calculated to analyze the differential distribution of deep crustal structural activity. Four indicators, including the minimum Moho depth, minimum crustal thickness, sum of Moho stretching factors, and sum of crustal stretching factors, were selected. Principal component analysis was applied to reduce the dimensionality of the multi-indicator system and obtain an oil and gas enrichment score for quantitative prediction of favorable prolific depressions. The deviation between the inverted Moho depth and seismic constraints was small; thus, the data effectively reflect the variations in the characteristics of each depression. The analysis revealed significant statistical features related to the minimum Moho depth/crustal thickness and the sum of Moho/crustal stretching factors associated with prolific depressions. Based on the oil and gas enrichment score, the depressions were classified into four categories related to their different deep crustal structural characteristics. Highly active Class Ⅰ, Class Ⅱ, and Class Ⅲ depressions are predicted to be favorable prolific depressions. This study expands the research on quantitatively predicting favorable prolific depressions in the Bohai Basin using the deep crustal structure and can contribute to reducing production costs and improving exploration efficiency in future explorations.

Key words: Bohai Basin, satellite gravity anomaly, deep crustal structure, Moho depth, crustal thickness, favorable prolific depression

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1 Introduction

Oil and gas exploration in the Bohai Sea, the largest petroliferous region offshore China, has been ongoing since the 1960s. However, despite its abundant resources, the proportion of proven reserves to total resources remains low, indicating significant potential for further exploration and development (Xue, 2018; Xue et al., 2020). Variations in the distribution of oil and gas resources exist among different petroliferous basins (He et al., 2023; Luo et al., 2023), as well as within different depressions within the same basin (Liu et al., 2014). The concepts of “oil-rich sag”; “gas-rich sag”; “prolific oil–gas depression”; “hydrocarbon-rich sag” and “prolific depression” have been successively proposed in research, and determining the hydrocarbon potential of these depressions is considered the primary problem for further fine-scale exploration of oil and gas resources (Han, 1983; Gong and Wang, 1997; Ye et al., 2012). The “prolific depression” concept was formally proposed in 1997 during a research project in the Bohai Bay Basin, and its main characteristics and classification criteria were summarized. This type of depression is defined as having a large area with continuous subsidence, thick dark mudstone, and favorable geochemical indicators and having undergone large-scale oil and gas generation, migration and accumulation. Such areas have been subject to a high degree of exploration, with significant amounts of documented oil and gas reserves, yet still possess considerable untapped potential for further exploration (Yuan and Qiao, 2002). Researchers have proposed various evaluation indicators, such as hydrocarbon generation intensity, resource abundance, resource scale, and proven reserves, for the assessment of prolific depressions (Yuan and Qiao, 2002; Zhao et al., 2004; Zhai and He, 2005; Li, 2006; Jia et al., 2008; Wen et al., 2011). Although there are numerous related studies at present, there are significant differences in the evaluation indicators and standards chosen by different scholars, and it is difficult to determine a prolific depression based on these

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evaluation indicators, which need to be determined based on multiple geological parameters. Overall, the research conducted on the activity of deep crustal structures and its correlation with oil and gas accumulation has provided valuable insights into the mechanisms governing the formation of oil and gas fields. This research has offered novel ideas and perspectives for the development of exploration strategies, particularly in basins such as the Bohai Basin.

Extensive research has established a strong correlation between the activity of deep crustal structures and the accumulation of oil and gas reserves. This correlation has played a crucial role in the formation of the Bohai Basin and its multilayer oil and gas reserves, creating favorable conditions for their development. The uplift of the Moho and the presence of weak zones in the crustal structure contribute to crustal subsidence, leading to the formation of large sedimentary areas that facilitate the preservation of the elements essential for accumulation, such as source rocks, reservoirs, caprocks, and various traps. Furthermore, the thinning of the crystalline crust and the active interaction between the crust and the mantle provide the necessary deep materials and energy for the accumulation of oil and gas, as well as the generation and evolution of hydrocarbons from sedimentary organic matter. This dynamic geological environment promotes the formation of oil and gas fields (Teng et al., 1983; Jin et al., 2003). Researchers, such as Shao et al. (1999), have discovered that certain characteristic parameters of the activity of deep crustal structures exhibit a consistent relationship with the degree of oil and gas enrichment in petroliferous basins. They have successfully utilized this relationship to evaluate and rank the oil and gas reserves of the basin and individual tectonic units. This method has proven effective in identifying the main exploration targets for oil and gas fields in the early stages of exploration. In a recent study by Zhang et al. (2023a), the relationship between the Moho uplift and oil and gas reserves in the seas offshore China and adjacent areas was investigated. The study concluded that basins with significant fluctuations in the Moho uplift are more likely to contain oil and gas reserves. This finding suggests that analyzing the distribution characteristics of the Moho depth and crustal thickness can be used as a valuable tool in identifying prolific depression areas, thereby simplifying the determination of exploration targets.

In recent years, scholars have made significant progress in studying the Moho depth and crustal thickness in the Bohai Basin and its adjacent areas. Various methods have been employed to determine the spatial variations in the Moho depth and crustal thickness using data recorded by seismic networks. These methods include the H-k receiver function stacking method and three-dimensional tomography method (Li et al., 2006; He et al., 2014; Zhang et al., 2015; Wang et al., 2017a). Additionally, some inversion work has been carried out based on seismic profile data to further understand structural aspects (Yang et al., 2000; Lai et al., 2007). Several seismic profiles passing through the basin were conducted in 2010 (Zhi, 2012; Hao et al., 2013), 2011 (Pan, 2013), and 2013 (Li et al., 2015). In addition, Xu et al. (2011) performed a 2.5-dimensional gravity and magnetic inversion of the crustal structure near the 2010 sea-land joint deep seismic profile to analyze the changes in Moho depth and crustal thickness along the profile. However, due to the sparse distribution of seismic stations, particularly in the Bohai Basin, and the limited number of seismic profiles, the resolution of the interpretation results based solely on seismic data is limited (Jiang et al., 2014). In contrast, gravity data allow for full coverage of the study area and have denser measurement points than the data derived from seismic stations. Therefore, conducting research based on gravity data, combined with constraints from seismic interpretation results, is advantageous for better understanding the distributions of Moho depth and crustal thickness in the Bohai Basin (Xing et al., 2002; Wu et al., 2014). To obtain detailed information on the spatial distribution of the Moho depth and crustal thickness, scholars have utilized various inversion methods, including three-dimensional inversion (Liu et al., 1996; Lu et al., 1999; Hu et al., 2016), the harmonic series method (Jiang et al., 2013), the Parker-Oldenburg method (Jiang et al., 2014, 2017; Guan et al., 2016), the convolution method based on the flexure isostasy model (Guan et al., 2016), and the introduction of a depth-weighted variable density function for interface inversion (Chen et al., 2019). While some studies have focused on the Bohai Basin and obtained large-scale inversion results, there are variations in the final distributions of Moho depth and crustal thickness. Therefore, further research is necessary to obtain reliable and comprehensive information on the Moho depth and crustal thickness through the use of gravity anomaly data sources, constraints on Moho depth, methods for extracting Moho gravity anomalies, and the selection of residual density.

In summary, the existing research primarily focuses on understanding the relationship between crustal thickness and oil and gas reserves in the basin. However, there is a lack of quantitative research on the relationship between crustal thickness and oil and gas reserves in depressions. Additionally, the accuracy of Moho depth and crustal thickness measurements is limited. To address these limitations, this study utilizes satellite gravity data and terrain data provided by the Scripps Institution of Oceanography at the University of California, San Diego. By combining these data with information on the distribution of sedimentary layers, this study aims to improve the reliability of extracted Moho gravity anomalies and obtain the distribution of Moho depth and crustal thickness in the Bohai Basin. This study also proposes the use of quantitative evaluation indicators, such as the minimum value of crustal thickness (Moho depth) and the sum of the crustal stretching factor (Moho stretching factor). These indicators can be used to assess the strength of the activity of deep crustal structures and the oil and gas reserves in each depression. With these indicators, this study aims to predict the locations of prolific depressions.

2 Data and methods

2.1 *Terrain and gravity data*

The terrain data (Fig. 1) and satellite gravity anomaly data (Fig. 2) used in this study are sourced from the Global Satellite Gravity Anomaly Database (Sandwell et al., 2014) maintained jointly by David T. Sandwell and Walter H. F. Smith. The specific version numbers of the two datasets are V 23.1 and V 31.1, respectively. The terrain data have a spatial resolution of 1′× 1′. In the sea area, the gravity data also have a resolution of 1′× 1′, and its total accuracy is approximately 3.03 mGal. On land, the gravity data have a network size of 5′× 5′, and its total accuracy is approximately 4.125 mGal (Sandwell et al., 2014, 2021). Furthermore, Zhang et al. (2023b) conducted a comparative evaluation of five versions of satellite altimetry gravity data from three different sources in the eastern part of the Philippine Sea in the Western Pacific Ocean. According to their evaluation, the accuracy of satellite altimetry gravity data in the V29.1 version of the Global Satellite Gravity Anomaly Database is relatively high, and the standard deviation between the satellite altimetry gravity data and shipborne gravity data is less than 1 mGal. The minimum

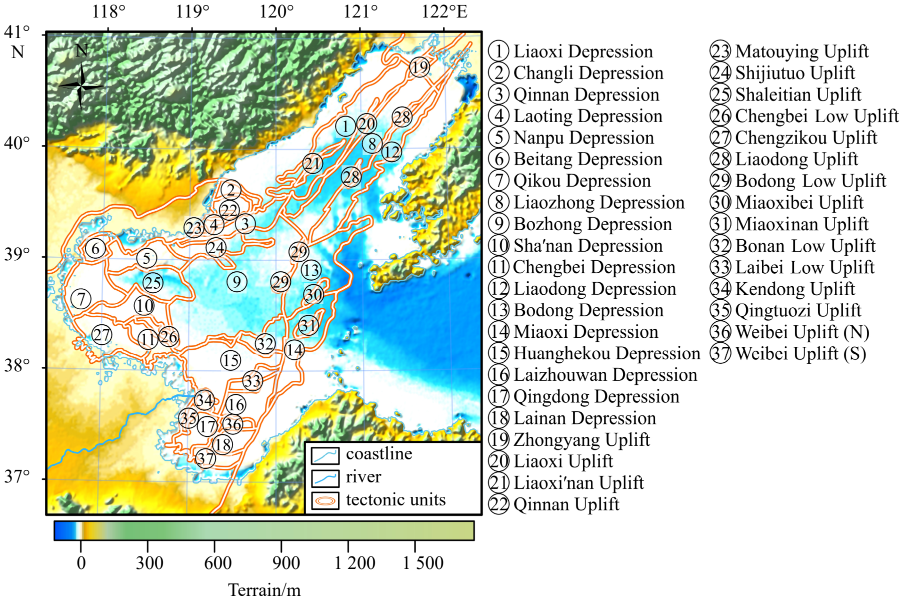

Fig. 1. Terrain in the Bohai Basin (tectonic units according to Xue et al., 2021).

curvature noise suppression method effectively improves the accuracy of satellite altimetry gravity data, reducing the deviation to approximately 0.5 mGal. Based on this, the accuracy and reliability of the updated V31.1 version of the data can also be inferred.

The satellite gravity anomaly magnitude in the Bohai Basin and its adjacent areas (Fig. 2) ranges from -78 m/s^2 to 94×10^{-5} m/s^2. The dominant anomaly trend is mainly northeast (NE), followed by northwest (NW) and east–west (E–W). In the sea area, the gravity values outside the Bohai Basin are relatively high, while inside the basin, they are lower due to the presence of low-density sediments. On land, mountainous areas exhibit higher gravity anomalies, whereas other regions are influenced by sedimentary layers, resulting in lower gravity anomalies.

2.2 *Moho depth constraints*

To enhance the accuracy of gravity inversion and improve the reliability of the obtained distribution, this study incorporates sea-land joint seismic detection data from 2010, 2011, and 2013 (Hao et al., 2013; Li et al., 2015; Liu et al., 2015) and Moho depth interpretation data obtained from seismic stations organized by He et al. (2014). A total of 195 constraint points are considered (Fig. 3). The Moho depth along the three survey lines is depicted in Fig. 4. The 2010 survey line traverses the southern Bohai Basin in a northwest (NWW) direction, passing primarily through the Qikou Depression, Sha'nan Depression, Bozhong Depression, Bonan Low Uplift, and Miaoxi Depression. The 2011 survey line cuts through the middle of the basin in a northeast (NE) direction, encompassing the Chengbei Depression, Chengbei Low Uplift, Bozhong Depression, Shijiutuo Uplift, Qinnan Depression, and Liaoxi Depression. The 2013 survey line crosses the central region of the basin in a northwest (NW) direction, predominantly crossing the Miaoxi Depression and Bozhong Depression. Notably, the Moho below the depressions generally exhibits uplifted characteristics. Among the three survey lines, the shallowest Moho position is observed within the interior of the Bozhong Depression, with a constrained depth of approximately 25 km. The 2010 survey line intersects the 2011 survey line in the Bozhong Depression, where the Moho is shallow, with a measured depth of approximately 28 km. Additionally, it intersects the 2013 survey line near the Miaoxi Depression, and the Moho in this area exhibits a small uplifted amplitude to a depth of 31 km.

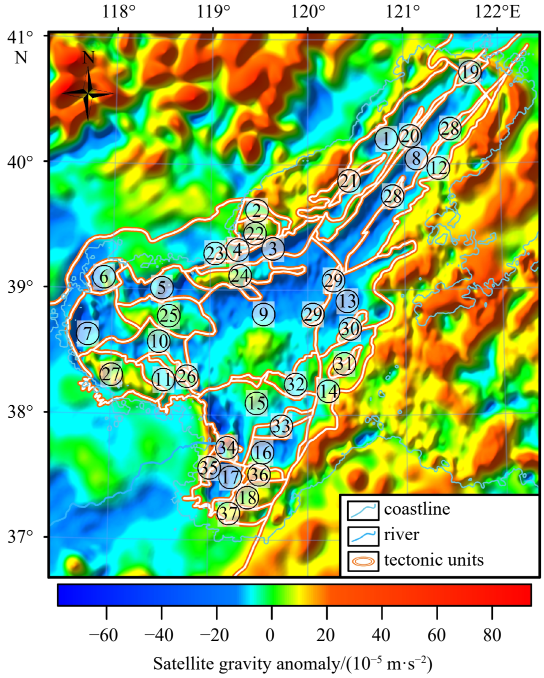

Fig. 2. Satellite gravity anomaly in the Bohai Basin.

2.3 *Moho depth inversion method*

To enhance the accuracy of the inversion results, this study adopts the Moho inversion method proposed by Zhang et al. (2023a). Specifically, it focuses on Moho gravity anomaly extraction and residual density calculation, aligning them with the specific conditions of the Bohai Basin. To improve the inversion accuracy, the study incorporates corresponding technical measures.

In this process, shallow gravity anomalies resulting from terrain and sedimentary layers are eliminated by utilizing the fast

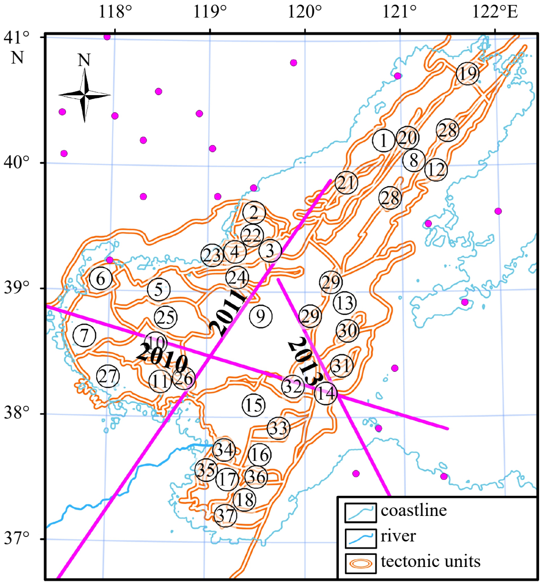

Fig. 3. Constraint points in the Bohai Basin (modified from Hao et al., 2013; He et al., 2014; Li et al., 2015).

solution of forward problems for the gravity field in a dual interface model (Wang and Pan, 1993). This step allows the extraction of gravity anomalies primarily influenced by the bottom interface of the Cenozoic strata in the sedimentary package (Fig. 5). Consequently, deep gravity anomalies are obtained (Fig. 6).

There is still a residual background value present between the gravity anomaly selected by the minimum curvature technique potential field data separation (Ji et al., 2015, 2019) and the gravity anomaly associated with the real Moho. Due to the limited constraint data in the Bohai Basin, the method proposed by Zhang et al. (2023a) is not suitable for removing the background value. In this paper, a new approach is adopted. According to the infinite-slab (Bouguer) formula, a linear relationship exists between the gravity anomaly and the slab thickness. This relationship is governed by the universal gravitational constant (G) and the residual density (Litinsky, 1989). Based on the assumption that the residual density is approximately constant, regression analysis is conducted using the Moho depth constraints and the gravity anomaly selected by potential field separation. The regression depth is then considered the approximate Moho depth, and the approximate Moho gravity anomaly is obtained through forward modeling. Next, the average difference between the two gravity anomalies at the Moho depth constraint points is calculated. This value represents the background value and is used to correct the Moho gravity anomaly (Fig. 7) to obtain the final result.

To achieve a more accurate representation of the residual density distribution closer to the real situation, this paper estimates the residual density distribution of the Moho beneath the Bohai Basin based on the quadratic function relationship between the density difference between sedimentary layers and the sedimentary basement with depth (Yu et al., 2017), as shown in Fig. 8.

Finally, the fast solution of inverse problems for the gravity field in a dual interface model was employed (Wang and Pan, 1993). This approach allowed the determination of the Moho depth by utilizing variable residual density inversion under the Moho depth constraints, as illustrated in Fig. 9.

3 Crustal thickness characteristics

3.1 *Moho depth*

The Moho depth in the Bohai Basin exhibits a range of variation from 26.52 km to 34.24 km, with an average depth of 30.58 km. Statistical analysis of the deviation between the constraint depth and the inversion depth demonstrates the influential role of the constraint points in Moho depth inversion. The average deviation between the two is merely 0.12 km, with a standard deviation of 0.8 km.

A comparison and mean square error (MSE) statistics of the inversion results using a constant residual density (–430 kg/m^3), variable residual density, and constraint depth from three seismic survey lines are presented in Fig. 10. It is evident that the utilization of variable residual density plays a crucial role in enhancing the accuracy of the inversion. The inversion depth using a

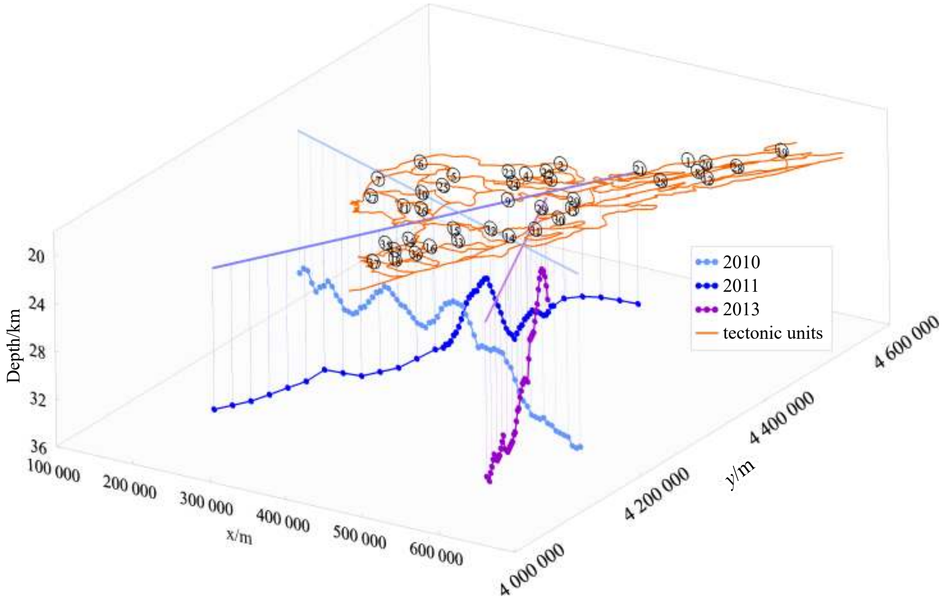

Fig. 4. The distribution of Moho depth constraints in the Bohai Basin.

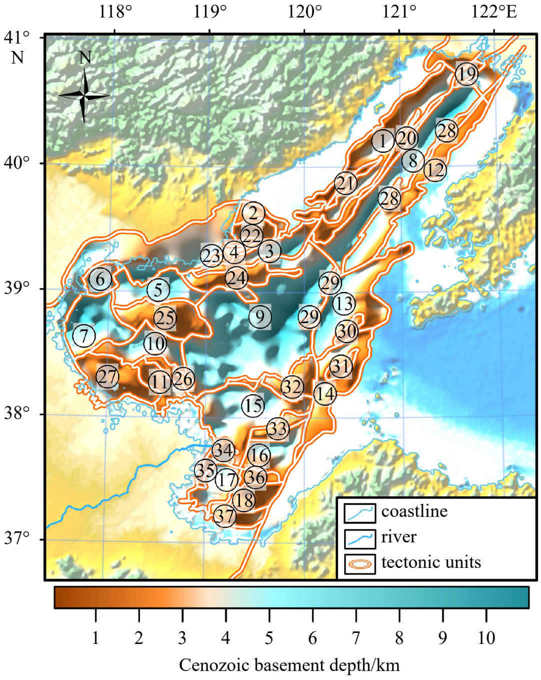

Fig. 5. Cenozoic basement depth in the Bohai Basin.

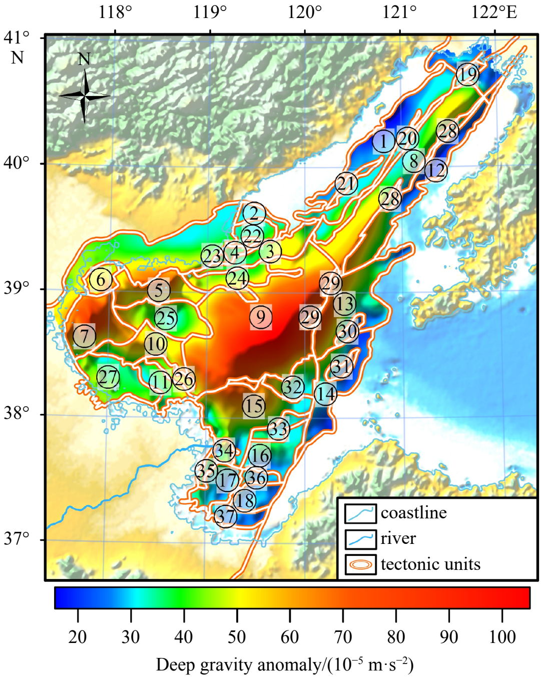

Fig. 6. Deep gravity anomalies in the Bohai Basin.

constant residual density substantially deviates from the constrained depth of the survey line in 2010 (Fig. 10a). However, upon adopting the variable residual density, the results in Qikou Depression, Bozhong Depression, and Bonan Low Uplift exhibit significant improvement, and the peak value of the constraint depth aligns more closely with the inversion depth using variable residual density. Furthermore, the overall trend and amplitude of the inversion depth using variable residual density demonstrate considerably greater consistency with the constraint depths of the survey lines in 2011 and 2013 (Figs10b and c).

3.2 *Crustal thickness*

By subtracting the depth of the sedimentary basement from the Moho depth, the crustal thickness of the Bohai Basin can be obtained (Fig. 11). The crustal thickness ranges from 16.30 km to 32.77 km, with an average thickness of approximately 26.57 km. This differs from the findings of previous studies that suggested that the thinnest crust in the Bohai Basin is approximately 28 km (Lu et al., 1999; Jiang et al., 2013; Zhang et al., 2015). This discrepancy arises is attributed to this study removed a portion of the shallow sedimentary layers and focused on the thickness of the crystalline crust.

The Moho uplift and crustal thinning zones correspond mainly to the depressions in the Bohai Basin, while the Moho depression and crustal thickening zones correspond primarily to the uplifted areas of the basin. This is consistent with the understanding proposed by Yu (1989) and Zhi (2012) regarding the “mirror” relationship between the Moho depth and tectonic units in the Bohai Basin. Significant NE-trending Moho uplift and crustal thinning can be observed in the Liaodong Bay Depression and the Bozhong Depression, while the Huanghua Depression exhibits a NW trend. In these basins, the Moho in the Bozhong Depression is the shallowest, and the crustal thickness is the thinnest, in agreement with the findings of Yu (1989), Liu et al. (1996), Lu et al. (1999), and Xing et al. (2002). Additionally, in the Liaozhong Depression, the centers of Moho uplift and crustal thinning are in the northern and southern segments, respectively, reflecting different deep-layer structural zones in these two sections. Furthermore, minor Moho uplift and crustal thinning features are observed in the Huanghekou Depression, the Laizhou Bay Depression, the Lainan Depression, and other areas, which differ from the understanding of a Moho depression in the Laizhou Bay Depression presented by Jiang et al. (2013) and Chen et al. (2019).

To analyze the relationship between the tectonic units and crustal structural characteristics in the Bohai Basin, a survey line (location shown in Fig. 11) is selected to create a crustal struc-

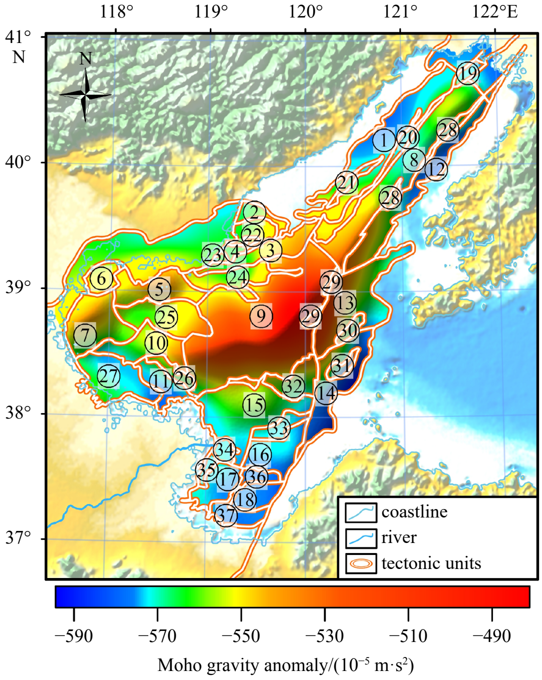

Fig. 7. Moho gravity anomaly in the Bohai Basin.

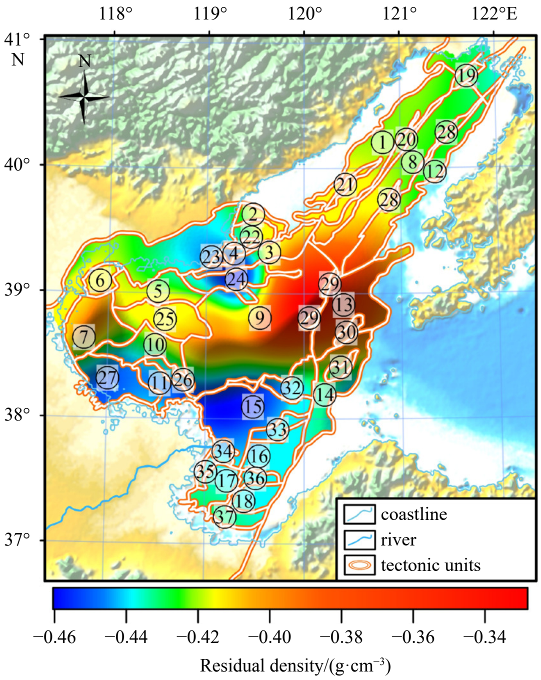

Fig. 8. Residual density in the Bohai Basin.

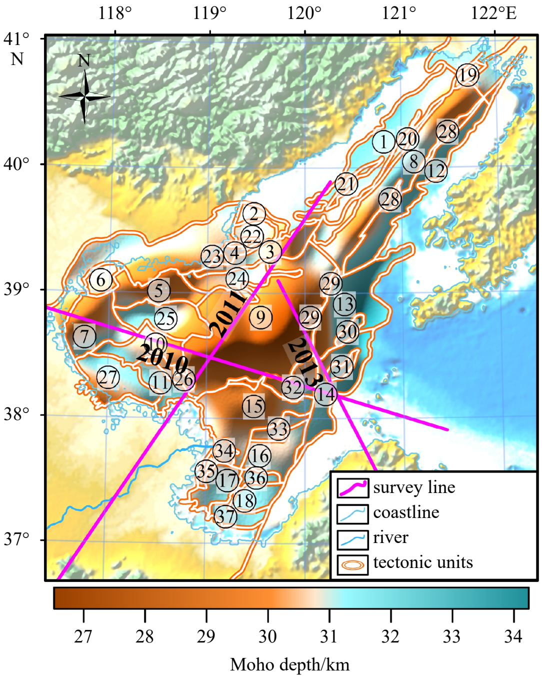

Fig. 9. Moho depth in the Bohai Basin.

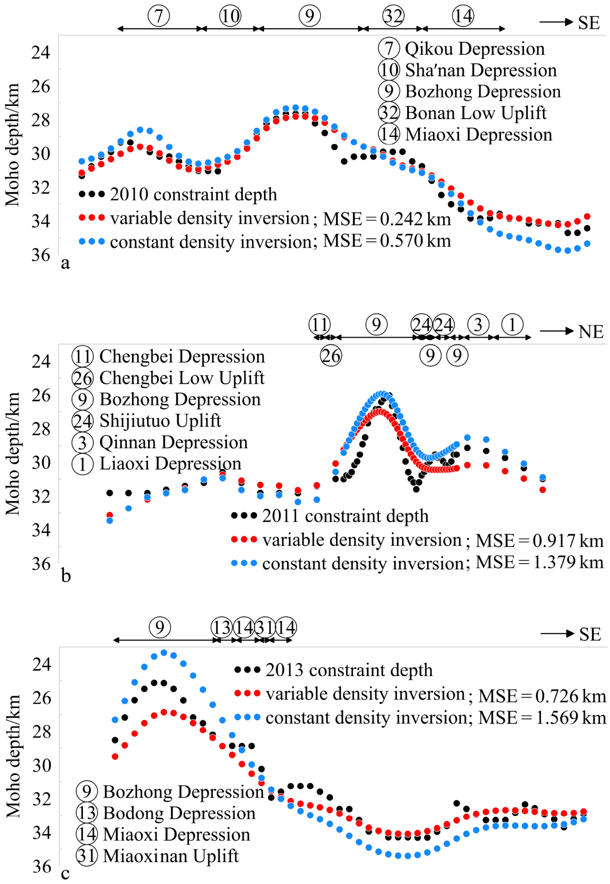

Fig. 10. Comparison of Moho depth in the Bohai Basin. a. survey line in 2010; b. survey line in 2011; c. survey line in 2013.

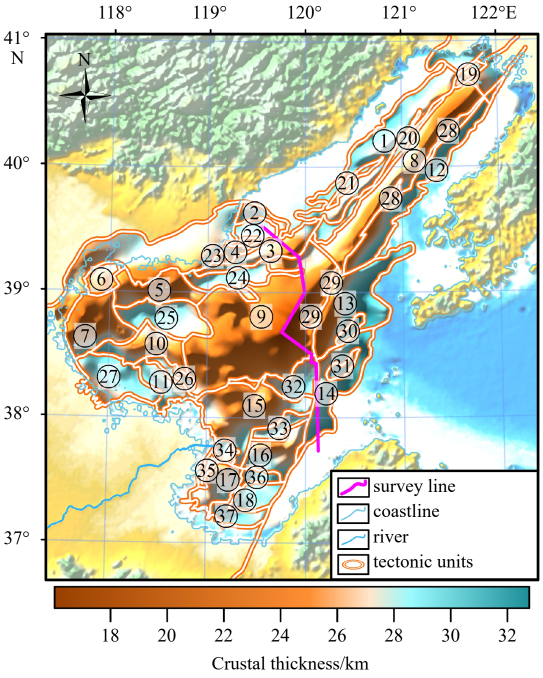

Fig. 11. Crustal thickness in the Bohai Basin.

ture profile, as shown in Fig. 12. The survey line traverses from east to west through the following regions: Miaoxi Depression, Bonan Low Uplift, Bozhong Depression, Shijiutuo Uplift, Qinnan Depression, and Qinnan Uplift. The Moho exhibits significant variations with a fluctuation of approximately 5 km, and the amplitude of crustal thickness change is approximately 16 km. There are two prominent Moho uplifts and crustal thinning centers, corresponding to the thick Cenozoic sediments in the Qinnan Depression (with a maximum thickness of approximately 8 km) and Bozhong Depression (with a maximum thickness of approximately 11 km). In particular, the Moho beneath the Bozhong Depression is the shallowest, and the area of upper mantle uplift is large. Conversely, in regions with thinner Cenozoic sediments,

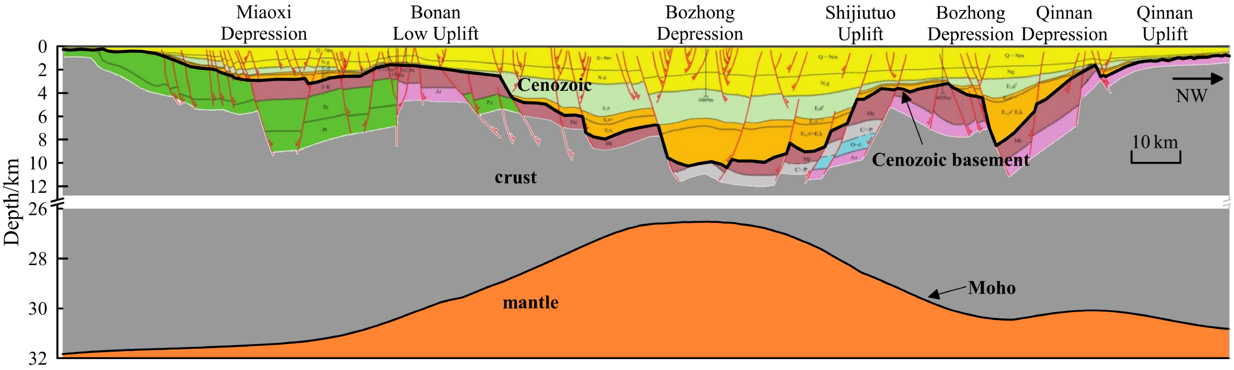

Fig. 12. Profile of the crustal structure in the Bohai Basin (seismic profile according to Zhu et al., 2010).

such as the Miaoxi Depression, Bonan Low Uplift, Shijiutuo Uplift, and Qinnan Uplift, significant Moho depression and crustal thickening can be observed. This indicates that the crustal stretching and thinning caused by the uplift of the upper mantle are conducive to the formation of large-scale sedimentary centers.

3.3 *Stretching factor*

The stretching factor is a crucial parameter used to quantify the degree of crustal stretching in extensional basins. It provides valuable insight into the degree of deformation within such basins. The stretching factor is directly proportional to the extent of crustal stretching, meaning that a higher stretching factor indicates a greater degree of extension. The formula for calculating the stretching factor is as follows:

$$\beta = t_0/t_e. \tag{1}$$

In the equation, t_0 represents the initial crustal thickness, while t_e represents the present crustal thickness (McKenzie, 1978; Qiu et al., 2019). The selection of an appropriate initial crustal thickness is crucial for accurately calculating the stretching factor. Typically, the crustal thickness at the margin of a rift basin is considered the initial crustal thickness (Zhou et al., 2013; Liu et al., 2018). However, some scholars have utilized current crustal thickness, sediment thickness, and water depth data to estimate the initial crustal thickness, accounting for variations across different locations (Wang et al., 2017c).

In this study, the concept of the stretching factor is also applied to the Moho depth. By calculating both the Moho stretching factor and the crustal stretching factor, it is possible to gain a deeper understanding of the degree of upper mantle uplift and the thinning degree of the stretched crust within a basin (Zhang et al., 2012). Zhu et al. (2012) conducted an analysis along the Lijin-Datong-Otog profile, an east-west traverse across the North China Craton. Their findings suggest that the western part of the profile exhibits a flat stratified crustal structure with the characteristics of cratonic crust. As a result, a Moho depth of 40 km and an initial crustal thickness of 40 km are selected for this study. Subsequently, the Moho stretching factor and the crustal stretching factor are calculated using Eq. (1) and the results are illustrated in Fig. 13.

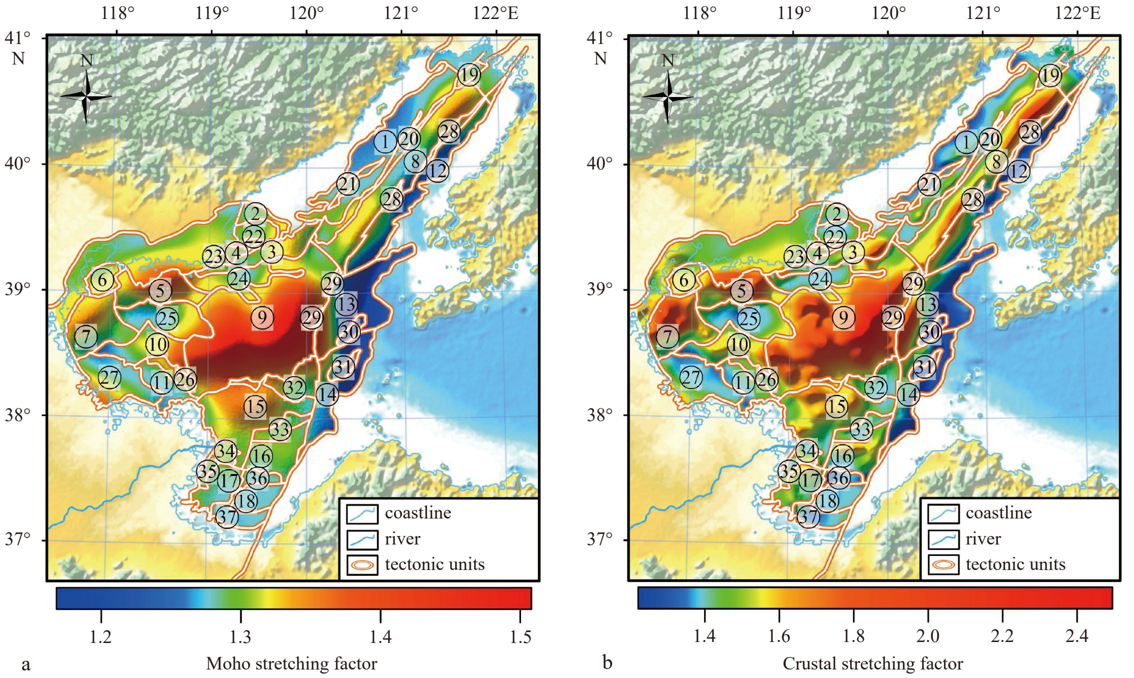

Fig. 13. Distributions of stretching factor results. a. Moho stretching factor; b. crustal stretching factor.

4 Prediction of prolific depression

The formation of large oil and gas fields is a complex process controlled by various factors, including the existence of high-quality source rocks, favorable reservoirs, effective caprocks, and specific configurations of source–reservoir or source–reservoir–cap assemblages (He et al., 2021). However, it is insufficient to solely consider sedimentary cover conditions when exploring for oil and gas, as the structural characteristics of deep crustal structures also play a significant role in the formation and migration of hydrocarbons. Studies have revealed a close relationship between the distribution of oil and gas reserves and the characteristics of the deep crustal structure within a basin. These characteristics are often characterized by a thinner crystalline crust and a stronger influence of the mantle on the crust (Shao et al., 1999). The formation of the extended Bohai Basin can be attributed to the subduction of the Pacific plate beneath the East Asian continent during various periods, leading to lithospheric dissolution, upwelling of the asthenosphere, crustal stretching, and crustal thinning. During this geological process, crustal and mantle materials were driven upward along deep faults through diapirism, providing abundant materials and energy for the formation of oil and gas (Cox and Engebretson, 1985; Maruyama et al., 1997; Zhu et al., 2004; Wan et al., 2009).

The heterogeneity in crustal movement within the Bohai Basin has led to significant variations in the distribution characteristics of deep crustal structures, including the Moho depth, crustal thickness, Moho stretching factor, and crustal stretching factor, among different tectonic units. These variations reflect the differential distribution of geological conditions for oil and gas reserves. In their recent research, Zhang et al. (2023a) emphasized that the fluctuation in Moho depth is a key factor contributing to the differences in oil and gas reserve distributions among different basins. In this study, the research focuses on the statistical analysis of the area of each depression within the Bohai Basin, as well as the maximum, minimum, and average values of the deep crustal structural characteristics. The aim is to identify indicators that exhibit strong consistency with existing geological information. Subsequently, principal component analysis (PCA) is employed to quantitatively evaluate the degree of oil and gas reserve presence within each depression.

4.1 *Statistical characteristics of crustal thickness*

The Moho depth and crustal thickness are calculated for each depression, and the maximum and minimum values indicate the variation in Moho depth and the degree of crustal thinning or thickening within each depression. The depressions are then sorted based on the minimum increase in Moho depth or crustal thickness. The ranges of these values are illustrated in Figs 14 and 15.

The distributions of Moho depth and crustal thickness exhibit significant variations among different depressions, with the Bozhong Depression showing the most distinct characteristics. The Bozhong Depression stands out with a minimum Moho depth of 26.5 km, which is shallower than that of all other depressions, and a minimum crustal thickness of 16.0 km, indicating significant crustal thinning. This suggests that the Bozhong Depression is located at the epicenter of upper mantle uplift, crustal stretching, and thinning within the Bohai Basin. In the Bodong Depression, the minimum Moho depth is 28.4 km, which is shallower than that in other depressions except for the Bozhong De-

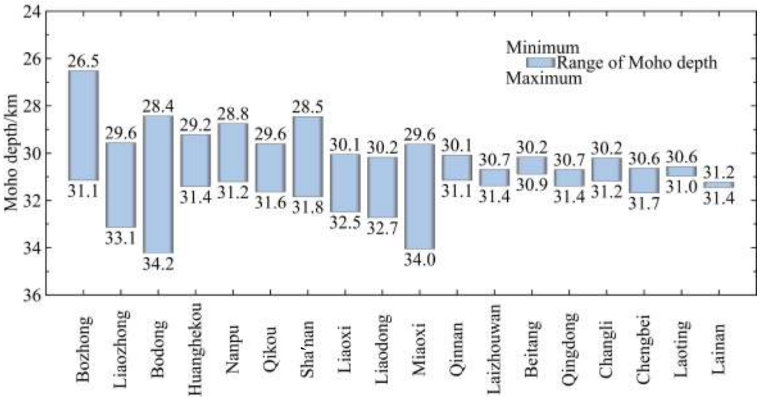

Fig. 14. Statistical results of Moho depth within various depressions in the Bohai Basin.

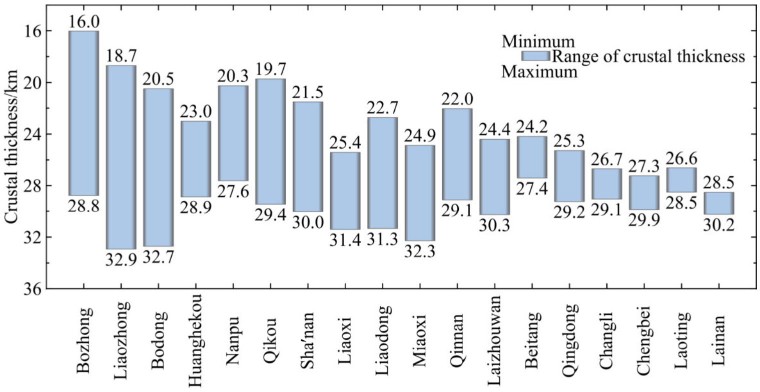

Fig. 15. Statistical results of crustal thickness within various depressions in the Bohai Basin.

pression, indicating notable Moho uplift. Furthermore, the minimum crustal thickness in the Liaozhong Depression is 18.7 km, which is thinner than that in other depressions except the Bozhong Depression, signifying a pronounced degree of crustal stretching and thinning. Additionally, the Moho is relatively shallow in the Sha'nan Depression, Qikou Depression, Nanpu Depression, and Huanghekou Depression (with minimum values of less than 30 km), which also feature thin crustal thicknesses (with minimum values of less than 23 km). In contrast, the Changli Depression, Laoting Depression, Chengbei Depression, Qingdong Depression, and Lainan Depression exhibit deeper Moho depths (with minimum values exceeding 30 km) and relatively thicker crustal thicknesses (exceeding 25 km). These variations can be attributed to the dynamic mechanisms associated with the subduction of the paleo-Pacific plate and the subsequent alteration of the North China Craton. Consequently, this led to the destruction of the craton's eastern segment and the emergence of localized disparities in crustal structure (Zhu et al., 2012).

The Moho stretching factor and crustal stretching factor were calculated for each depression. The stretching factor at each calculation point indicates the fluctuation of the Moho or the degree of crustal thinning/thickening. The sum of the stretching factors at all calculation points within each depression provides a comprehensive measure of the three-dimensional changes in the Moho and crust. The depressions were then sorted based on the decreasing sum of stretching factors. The distribution of the amplitude and average value of these factors is illustrated in Figs 16 and 17.

The differences in crustal structure within the Bohai Basin are also reflected in the Moho and crustal stretching factors, with the values of the Bozhong Depression standing out as the most prominent. The mean value and sum of the Moho stretching factor in the Bozhong Depression are 1.40 and 14.16 × 10^3, respectively, surpassing all other depressions. Similarly, the average value and sum of crustal stretching factors in the Bozhong Depression are 1.79 and 18.19 × 10^3, respectively, which are higher than those in other depressions. These indicators highlight that the Bozhong Depression is situated at the heart of the Bohai Basin, where the upper mantle exhibits significant variations in uplift and where crustal stretching and thinning are most pronounced. Although the average values of the Moho and crustal stretching factors in the Liaozhong Depression are not as prominent, the overall degree of variation in the Moho and crust is second only to that of the Bozhong Depression (with the sums of the Moho and crustal stretching factors being 5.55 × 10^3 and 6.76 × 10^3, respectively). Additionally, significant variations in the Moho and crustal stretching factors can be observed in the Liaoxi Depression, Huanghekou Depression, Bodong Depression, and Qikou Depression (with a sum of Moho stretching factors of $\geqslant 3.00 \times 10^3$ and a sum of crustal stretching factors of $\geqslant 3.81 \times 10^3$). In contrast, the Moho depths and crustal thicknesses of the Qingdong Depression, Chengbei Depression, Lainan Depression, Beitang Depression, Changli Depression, and Laoting Depression exhibit minimal variation (with a sum of Moho stretching factors of $\leqslant 1.47 \times 10^3$ and a sum of crustal stretching factors of $\leqslant 1.68 \times 10^3$). These indicators further support the understanding of the heterogeneity in Moho undulation and crustal thinning/thickening within the region.

Based on the aforementioned statistical results, it is evident that the Bozhong Depression is located at the center of upper

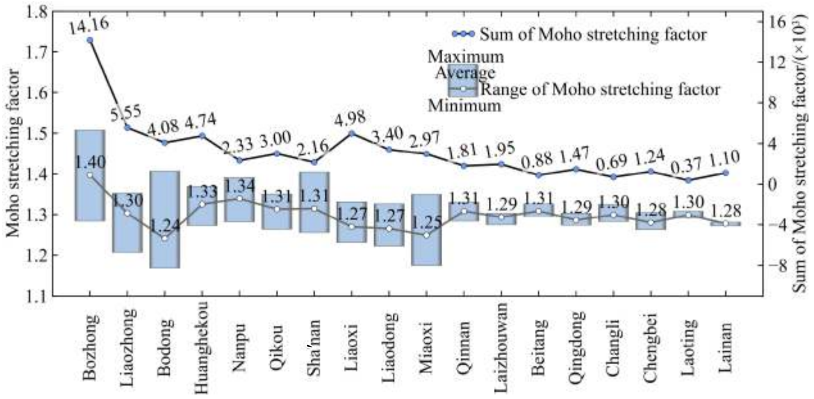

Fig. 16. Statistical results of the Moho stretching factors within various depressions in the Bohai Basin.

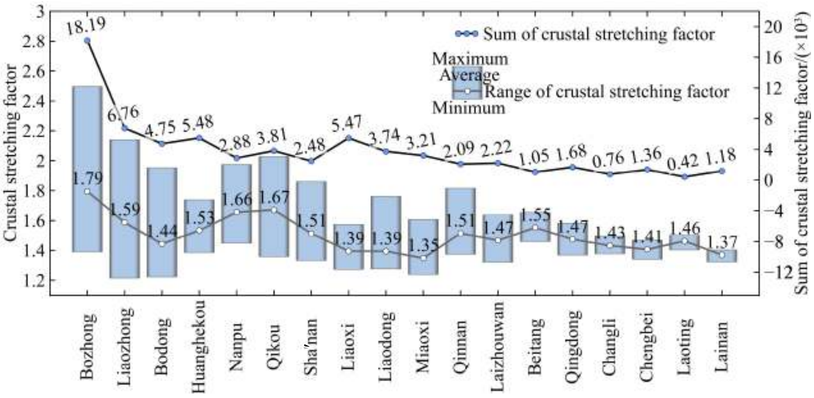

Fig. 17. Statistical results of the crustal stretching factors within various depressions in the Bohai Basin.

mantle uplift and crustal stretching and thinning within the Bohai Basin. This depression experienced the most significant changes in the Moho uplift and crustal stretching and thinning, indicating strong activity in the deep crustal structure. The Liaozhong Depression, Bodong Depression, Qikou Depression, and Huanghekou Depression represent secondary centers of upper mantle uplift and crustal stretching and thinning. These depressions also exhibit relatively substantial changes in Moho uplift and crustal stretching and thinning. On the other hand, the Qingdong Depression, Chengbei Depression, Lainan Depression, Changli Depression, and Laoting Depression exhibit low degrees of Moho uplift and crustal thinning. Moreover, the overall change in these depressions is minimal, indicating weak activity in the deep crustal structure.

4.2 *Prediction of prolific depressions*

The Bozhong Depression is the most significant prolific depression in the Bohai Basin (Zhang, 2000; Wang et al., 2017b; Xue et al., 2020). Its oil and gas enrichment is well reflected by the statistical indicators used in this study, primarily represented by the lowest value of crustal thickness (Moho depth) and the highest value of the sum of crustal (Moho) stretching factors. Based on the above four indicators, this paper adopts the PCA method to comprehensively evaluate the oil and gas enrichment scores of 18 depressions. A higher score indicates stronger deep crustal structural activity and a greater potential for oil and gas accumulation in the depression. This study applies PCA using SVD decomposition of the covariance matrix (Guo et al., 2020). Each indicator is subtracted by its mean value, and then the covariance matrix is calculated. SVD is used to compute the eigenvalues and eigenvectors of a 4 × 4 covariance matrix. The resulting eigenvectors corresponding to the maximum eigenvalue of the covariance matrix are multiplied with an 18 × 4 statistical indicator matrix, resulting in a one-dimensional vector. This vector is then normalized to obtain the oil and gas enrichment scores.

K-means (MacQueen, 1967) was performed on the rich oil and gas enrichment scores of each depression, resulting in four groups. The clustering center for the first group (Class Ⅰ) was 1.00, which included only Bozhong Depression (with a score of 1.00). The clustering center for the second group (Class Ⅱ) was 0.42, which included the Liaozhong Depression (0.49), Bodong Depression (0.46), Huanghekou Depression (0.40), Nanpu Depression (0.39), Qikou Depression (0.38), and Sha’nan Depression (0.38). The clustering center for the third group (Class Ⅲ) was 0.30, which included the Liaoxi Depression (0.33), Liaodong Depression (0.31), Miaoxi Depression (0.29), and Qinnan Depression (0.28). The clustering center for the fourth group (Class Ⅳ) was 0.16, which included the Laizhouwan Depression (0.21), Beitang Depression (0.21), Qingdong Depression (0.18), Changli Depression (0.16), Chengbei Depression (0.15), Laoting Depression (0.13), and Lainan Depression (0.09). Among them, the Class Ⅰ, Class Ⅱ and Class Ⅲ depressions exhibit vigorous deep-level tectonic activity, with upwelling of the upper mantle providing abundant material and energy for the generation of oil and gas. Crustal stretching and thinning processes resulted in thicker sedimentary layers, creating favorable conditions for the generation and accumulation of oil and gas reserves. Therefore, these depressions have higher oil and gas enrichment scores and are considered the most favorable depressions for oil and gas exploration and production. Notably, the Bozhong Depression has a significantly higher enrichment score than other depressions, aligning with its recognition as the most prolific depression in the Bohai Basin during actual exploration (Xie et al., 2018). On the other hand, the Class Ⅳ depressions exhibit weaker deep-level tectonic activity and consequently lower oil and gas enrichment. Therefore, reduced investment in production can be considered for exploration in these depressions.

Zhang (2000) pointed out that due to the influence of the deep-seated fault, the oil and gas in the Bohai Basin are mainly distributed in prolific depressions such as the Bozhong Depression, Liaozhong Depression, Huanghekou Depression, and Qikou Depression. Based on resource abundance indicators and basin resource scale predictions, Yuan and Qiao (2002) identified the Liaoxi Depression, Liaodong Depression, Nanpu Depression, and Qikou Depression as prolific depressions. Zhang et al. (2013) used oil-source tracing and seismic facies analysis to identify potential prolific depressions and confirmed that the Liaoxi Depression is a prolific depression. Based on the study of source rock generation and evolution of prolific depressions, Yu et al. (2021) confirmed that the Bodong Depression and Miaoxi Depression have good exploration prospects. This study confirms the previous understanding of oil and gas enrichment in these depressions based on the evaluation of deep crustal structural activity: The Bozhong Depression, Liaozhong Depression, Bodong Depression, Huanghekou Depression, Liaoxi Depression, Liaodong Depression, and Miaoxi Depression, which are distributed along the Tancheng-Lujiang Fault in the NNE direction, as well as the Nanpu Depression, Qikou Depression, and Sha'nan Depression, which are distributed along the Lanliao-Yanshan Fault in the NE direction, all have high oil and gas enrichment, mostly belonging to Class Ⅰ and Class Ⅱ depressions. At the same time, this study further evaluates the enrichment of oil and gas in other depressions within the basin and suggests that the Sha’nan Depression, Liaodong Depression and Qinnan Depression are also potential targets for further oil and gas exploration.

5 Conclusions

In this paper, we utilize satellite gravity anomaly data, the minimum curvature potential field separation technique, the correlation analysis technique, the variable residual density estimation technique, and the fast solution of forward and inverse problems for gravity fields in a dual interface model. These methods are employed to accurately and comprehensively determine the Moho depth, crustal thickness, and stretching factors of the Bohai Basin, thereby providing a detailed and precise depiction of its geological features. Through statistical analysis of the depression areas and the maximum, minimum, and average values of deep crustal structural characteristics, we have gained the following insights.

(1) During the formation of the Bohai Basin, the subduction and collision of the ancient Pacific plate led to the disruption of the originally flat and stable stratified crustal structure. This resulted in uplifting of the upper mantle and thinning of the crust. The Moho depth in the basin ranges from 26.52 km to 34.24 km, with an average depth of 30.58 km. The crustal thickness varies from 16.30 km to 32.77 km, with an average thickness of 26.57 km. The overall distribution of the Moho depth and crustal thickness follows a NE trend.

(2) Each depression within the Bohai Basin exhibits distinct variations in the distribution of four deep crustal structural features: minimum Moho depth, minimum crustal thickness, sum of Moho stretching factors, and sum of crustal stretching factors. Among them, the Bozhong Depression exhibits the highest level of crustal structural activity, indicating its central location in terms of upper mantle/Moho uplift and crustal stretching and

thinning.

(3) The activity of the deep crustal structure provides favorable geological conditions for the accumulation of oil and gas. To assess the oil and gas potential, principal component analysis was employed to reduce the dimensionality of the four characteristics of the deep crustal structure. The resulting dimensionally reduced data can be used as indicators of oil and gas enrichment within each depression. Based on these indicators, the depressions in the Bohai Basin are divided into three categories. Depressions with higher scores exhibit stronger activity within the deep crustal structure and are associated with higher oil and gas enrichment. The Class Ⅰ depressions (Bozhong Depression), Class Ⅱ depressions (Liaozhong Depression, Bodong Depression, Huanghekou Depression, Nanpu Depression, Qikou Depression, and Sha’nan Depression) and Class Ⅲ depressions (Liaoxi Depression, Liaodong Depression, Miaoxi Depression, and Qinnan Depression) are favorable for oil and gas exploration and suitable for further investigation. The Class Ⅳ depressions (Laizhouwan Depression, Beitang Depression, Qingdong Depression, Changli Depression, Chengbei Depression, Laoting Depression, and Lainan Depression), on the other hand, have less potential and may require reduced investment.

(4) In this paper, the prediction of prolific depressions is primarily based on analyzing the differential distribution of the deep crustal structure, specifically focusing on the Moho depth and crustal thickness. Additionally, the prediction results exhibit a strong correlation with the distribution of deep faults. However, the formation of prolific depressions is influenced by a multitude of factors. Therefore, it is recommended to extend this approach to analyze other control factors in future studies. By further scrutinizing the content of this paper, it is possible to enhance the judgment of prolific depressions and conduct more practical exploration work to validate the prediction results.

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