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The Depth Limit for the Formation and Occurrence of Fossil Fuel Resources

Xiongqi Pang[1,2] *, Chengzao Jia[1,3], Kun Zhang[2] **, Maowen Li[4], Youwei Wang[2,5], Junwen Peng[6], Boyuan Li[2], and Junqing Chen[1,2]

[1]State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing, 102249, China
[2]College of Geosciences, China University of Petroleum, Beijing, 102249, China
[3]Research Institute of Petroleum Exploration and Development, PetroChina, Beijing, 100083, China
[4]State Key Laboratory of Shale Oil and Gas Enrichment Mechanisms and Effective Development, SINOPEC Exploration and Production Research Institute, Beijing, 100083, China
[5] Department of Geosciences and Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, Netherlands
[6]Bureau of Economic Geology, University of Texas at Austin, Austin, TX 78713, USA

Correspondence to: Xiongqi Pang (pangxq@cup.edu.cn); Kun Zhang (zhangk.cupb@gmail.com)

Abstract. Fossil resources are valuable wealth given to human beings by nature. Many mysteries related to them have been revealed such as the origin time and distribution area, but their vertical distribution depth has not been confirmed for people's different understanding of their origin and the big depth variations from basin to basin. Geological and geochemical data of 13,634 source rock samples from 1,286 exploration wells in six representative petroliferous basins are examined to study their Active Source Rock Depth Limits (ASDL), defined in this study as the maximum burial depth of active source rocks beyond which the source rocks no longer generate or expel hydrocarbons and become inactive, to identify the maximum depth for fossil fuel resources distribution. Theoretically, the maximum depth for the ASDLs of fossil fuel resources ranges from 3,000 m to 16,000 m, while their thermal maturities (Ro) are almost the same with Ro≈3.5±0.5%. A higher heat flow and more oil-prone kerogen are associated with a shallower ASDL. Active source rocks and the discovered 21.6 billion tons of reserves in six representative basins in China and 52,926 oil and gas reservoirs in the 1,186 basins over the world are found to be distributed above the ASDL, illustrating the universality of such kind of depth limit. The data are deposited in the repository of the PANGAEA database: https://doi.pangaea.de/10.1594/PANGAEA.900865 (Pang et al., 2019).

Keywords: Fossil fuels; Conventional and unconventional hydrocarbons; Sedimentary basin; Active source rock depth limit

1 Introduction

Fossil fuel resources, including coal, conventional and unconventional hydrocarbons, account for 85.5% and 86.9% of the primary energy consumption in 2016 of the world and China (B.P. Global, 2017), respectively. Because of their indispensable role in boosting economy, many mysteries related to fossil fuel resources have been uncovered, including their spatial distribution in sedimentary basins (Tissot & Welte, 1978; Wang et al., 1997; Gautier et al., 2009) and their temporal

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distribution through about 1.6 billion years in the geological history (Wang et al., 2016). However, the vertical distribution of fossil fuel resources, i.e. the maximum depth, has not been confirmed because of people's different understanding of their origin and their big depth variations from basin to basin (Kennedy et al., 2002; Peters et al., 2005; Pang et al., 2015). This study discussed the related problems.

As global demand for energy keeps rising, fossil fuels exploration is rapidly expanding to deep Earth (Dyman et al., 2002). Currently, the deepest commercial hydrocarbon reservoir worldwide is located in the basin of Mexico Gulf with a depth of 11,945 m (including water depth) (Transocean, 2009). In China, deep (> 4,500 m) and ultra-deep (> 6,000 m) oil and gas reservoirs were mainly found in the Tarim basin and they take up more than 90% of the total proved reserves in the basin (Pang et al., 2015). In order to boost oil and gas supply to support fast economic growth, China has funded programs developing 10,000 m scientific drilling rigs, and funded the National Basic Research Program (973 Program) to probe deep hydrocarbon accumulations (Jia et al., 2016). One big challenge for deep oil and gas exploration comes from the great variety of reservoir depth and the uncertainty it poses to oil and gas resources assessment. In some basins, dry layers, objective strata containing no oil or gas, are prevalent at a depth of 4,500 m or less, whereas in some other basins, the maximum burial depth for oil and gas accumulation is predicted to go beyond 10,000 m. To date, the maximum depth to which fossil fuels can be formed and preserved in the Earth's crust is still a mystery. Researchers supporting the abiogenic petroleum origin believe that the maximum depth is much deeper than the depth of petroliferous basins itself (Gold, 1993; Kenney et al., 2002), but proponents of the biogenic origin suggest that the maximum depth is controlled by the depth of source rocks which generate and expel oil and gas in sedimentary basins (Tissot & Welte, 1978; Durand, 1980; Hunt, 1996). Different answers have been given in previous research (White, 1993; Bloch et al., 2002; Ajdukiewicz et al., 2010).

To solve this mystery and to profoundly understand hydrocarbon generation and accumulation processes, this study selected six representative petroliferous basins which have the largest areas, the largest proved oil and gas reserves and the highest exploration degrees in China (Fig. 1, Table 1) to study the maximum depth for fossil fuel resources distribution. This study did not take the abiogenic petroleum origin into account for the reason that the genetic relationship between petroleum and organic matter in source rocks has been proved (Magoon & Dow, 1994; Peters et al., 2005) and no commercial petroleum reservoirs of abiogenic origins have been discovered so far (Kenney et al., 2002; Glasby, 2006; Höök et al., 2010; Selley & Sonnenberg, 2014). Geological and geochemical data of 13,634 source rock samples from 1,286 exploration wells in these basins have been examined, and the maximum depth for the formation and occurrence of fossil fuel resources have been identified, as well as the major factors influencing the maximum depth of active source rocks and their controlling on the fossil fuel resources distribution have been discussed.

Figure 1: Location of the six representative petroliferous basins and five coal-accumulation areas in China. The studied petroliferous basins, plotted on the China mainland, are pigmented with different colors according to their locations in China. The five coal-accumulation areas, bounded by large geological structural belts, are identified according to Zhu (2011).

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2 Materials and Methods

2.1 Study sites and data collection

We conducted this study regarding ASDLs in six representative basins in China, including the Songliao Basin and Bohai Bay Basin in the eastern China, Sichuan Basin and Ordos Basin in the central China, Tarim Basin and Junggar Basin in the western China. Within each basin, we utilized at least four different indicators reported in the next section (Characterization of ASDLs) to determine the ASDLs. The data necessary for identifying the ASDLs was obtained from PetroChina and Sinopec, respectively. The dataset can be accessed through the PANGAEA database: https://doi.pangaea.de/10.1594/PANGAEA.900865 (Pang et al., 2019). We further investigated the ASDLs of 52,926 reservoirs in 1,186 basins over the world according to the database of IHS (2010) to inspect its universality.

2.2 Characterization of ASDLs

The Active source rocks are sedimentary rocks rich in organic matter and capable of generating hydrocarbons. In a buried process, source rocks are activated and begin producing hydrocarbons at certain conditions, such as the generally regarded threshold temperature of 60 ˚C (Tissot & Welte, 1978; Peters, 1994). As the source rocks evolve further with increasing burial depth, the potential amounts of hydrocarbons that can be produced and expelled from the source rocks decreases and eventually goes to zero. The Active Source Rock Depth Limit (ASDL) is defined as the maximum burial depth of active source rocks beyond which the source rocks no longer generate or expel hydrocarbons and become inactive. In addition to the burial depth, ASDL can also be characterized by other critical conditions, such as the thermal maturity (Ro) of the source rocks.

The potential amounts of hydrocarbons that can be further generated from a source rock sample cannot be directly measured, but can be evaluated based on many experimentally measurable parameters, such as the atomic ratio of hydrogen to carbon (H/C) and oxygen to carbon (O/C) of the remaining organic matter in the source rocks. The generation of oil and gas from organic matter is the process of condensation of the aromatic nuclei that enriches carbon by deoxygenation and dehydrogenation. The process can be experimentally investigated by measuring the decrease in the H/C and O/C ratios (Tissot et al., 1974). In theory, kerogen eventually evolves into graphite with increasing thermal maturity with the H/C and O/C ratios drop to 0. This indicates that the active source rocks no longer produce hydrocarbons and thus reach the ASDL.

The Rock-Eval pyrolysis parameters can also be utilized to measure the ASDL such as the hydrocarbon generation potential index (“S_1 + S_2”/TOC). “S_1” is the amounts of hydrocarbons released from a source rock sample when it is heated from room temperature to 300 °C, and “S_2” is the amount released from 300 °C to 600 °C in Rock-Eval pyrolysis system. TOC is the measured total organic carbon in the source rock (Espitalie et al., 1985). The concept of hydrocarbon generation potential index was proposed by Pang et al. (2005) to measure the quantity of hydrocarbons that can be generated from a single unit of organic carbon. The hydrocarbon generation potential index of the source rocks first increases and then decreases with increasing burial depth. The turning point of hydrocarbon generation potential index corresponds to the

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hydrocarbon expulsion threshold (HET) which was proposed by Pang et al. (1997). It represents that the source rocks begin expelling hydrocarbons. As the hydrocarbon expulsion of the source rock increases, the hydrocarbon generation potential index of the source rock gradually depletes, and when the hydrocarbon generation potential index approaches zero, the source rock can no longer expel hydrocarbons and reaches the ASDL. During the evolution of hydrocarbon generation potential index, the hydrocarbon expulsion ratio (Qe), hydrocarbon expulsion rate (Ve) and hydrocarbon expulsion efficiency (Ke) of source rocks also change with regularity. Hydrocarbon expulsion ratio represents the amounts of hydrocarbons expelled from a single unit of organic carbon. Hydrocarbon expulsion rate represents the hydrocarbons expelled from a single unit of organic carbon when burial depth increases by 100 m, and the hydrocarbon expulsion efficiency represents the ratio of cumulative amounts of hydrocarbons expelled from source rocks to cumulative amounts of hydrocarbons generated. When the source rocks reach the state of ASDL, Qe and Ke approach the constant values and Ve approaches the value of zero.

In addition, hydrocarbon generation is the transformation of original organic matter (kerogen) to transitional compounds and finally to hydrocarbons (Behar, et al., 2006). Therefore, when the transitional compounds or the residual hydrocarbons (“S_1” or “A”) tend to disappear indicating that the hydrocarbon generation potential is exhausted. “A” is the amounts of hydrocarbons extracted by chloroform solution from a source rock sample. Because some non-hydrocarbon matter can also be extracted, “A” values are generally larger than “S_1” values. The residual hydrocarbon content index (“S_1”/TOC or “A”/TOC), representation of quantity of hydrocarbons that are retarded in a single unit of organic carbon, can therefore be used to measure the ASDL. Previous study (Pang et al., 2005) indicates that the source rocks entered hydrocarbon expulsion threshold when the residual hydrocarbon content index reached the maximum value and since then, such index began to decrease. The source rocks finally enter the state of ASDL when the residual hydrocarbon content index decrease to a minimum value. This study analysed trends of these parameters as a function of depth (D) or thermal maturity illustrated by measured vitrinite reflectance (Ro). The ASDL is thus represented as the level of D or Ro where the indexes of H/C, O/C, “$S_1 + S_2$”/TOC, “S_1”/TOC, “A”/TOC, and Ve approach zero, and Ke approaches a constant value.

3 Results and Discussions

3.1 ASDLs in the Six Representative Basins

In this study, we characterized the ASDLs in the six representative basins of China. The main text takes the Junggar Basin located in western China as an example to illustrate the process of characterization (Fig. 2). The same methods were applied to study all the major source rocks from the six representative basins, and the results are shown in Figs. S1–S5 and Table 2. Figure. 2a shows H/C ratios versus depth of source rock samples from the Junggar Basin. The average H/C ratio of a certain source rock layer decreases sharply at a depth of about 6,000 m, beyond which there are no samples with H/C ratios greater than 1.5. A dashed curve was drawn to envelope all the sample values. The intercept of the dashed line on the vertical axis marks the ASDL, which corresponds to D ≈ 8,350 m and Ro ≈ 3.0%. Figure. 2b shows the variation of residual

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hydrocarbon amounts in source rock samples, represented respectively by "A"/TOC or "S_1"/TOC, with burial depth. Initially, both the mean and the variance of the residual amounts increase with depth, because hydrocarbons are generated but not yet expelled out of the source rocks. A maximum is reached at a depth of 3,500 to 4,000 m or at Ro≈1.0%, which is corresponding the hydrocarbon expulsion threshold. With further increase of depth, the amount of residual hydrocarbon starts decreasing, and finally reaches zero at the ASDL of 7,850–7,960 m with corresponding Ro of 3.0%. Figure. 2c shows the change of hydrocarbon generation potential index, ("S_1 + S_2")/TOC, hydrocarbon expulsion ratio (Qe), hydrocarbon expulsion rate (Ve) and hydrocarbon expulsion efficiency (Ke) of the source rock samples with increasing burial depth. These results point to an ASDL of 8,200 m with corresponding Ro of 3.0%, in good agreement with the values obtained in Fig. 2a and 2b. Besides, the HET is determined to be D of 3,000 m and Ro of 0.9%, and the expulsion peak occurs at D of 4,500 m and Ro of 1.3%.

Figure 2: The identification of ASDL in the Junggar Basin using different indicators. a, the variation of H/C ratios with depth and identification of ASDL. b, the variation of residual hydrocarbon amounts (represented by "A"/TOC and "S_1"/TOC) with depth. c1, the variation of hydrocarbon generation potential index (represented by "S_1 + S_2"/TOC) with depth and identification of ASDL; c2, the variation of Qe with depth and identification of ASDL; c3, the variation of Ve with depth and identification of ASDL; c4, the variation of Ke with depth and identification of ASDL.

According to the results of ASDLs in the six representative basins (Table 2), three kinds of features of ASDLs can be drawn from them. First, the ASDLs of the same basin derived from the six indexes are same or very close in values. For example, the derived depths of the ASDL in the Junggar Basin vary from 7,850 m to 8,450 m with an average value of 8,168 m and a deviation of 7.6%. Second, ASDLs in different basins can be very different. ASDLs of the six representative basins range between 5,280 m and 9,300 m with an average value of 7,094 m and a deviation of >76%. Third, for all ASDLs of the six representative basins, the corresponding thermal maturities have much smaller variation than the depths. Ro values vary from 3.0% in the Junggar Basin to 4.0% in the Songliao Basin, with an average of 3.5% among the six basins and a deviation of 33.3% which is much smaller than the 76.1% deviation of the depths. This implies that ASDL is mainly controlled by the thermal maturity of source rocks. The average thermal maturity level of 3.5% can be regarded as the identification criterion for ASDL in general geological settings.

3.2 Major factors controlling ASDLs and their effects

3.2.1 Organic Matter Type

The original organic matter in source rocks, named as kerogen, is generally classified into three types based on its origin (Peters, 1994; Tissot et al., 1974). It has different organic element composition and different pyrolytic parameters, and therefore has different hydrocarbon generation potential. The hydrocarbon generation potential index of different type source

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rock samples from the representative basins are plotted in Fig. 3. Similarly, the dashed curves enveloping all the sample values indicates the varying trends of hydrocarbon generation potential of source rocks with different organic matter types. The trends of hydrocarbon generation potential index of different organic matter types varying with thermal maturity (Ro) are very similar: the index increases first and then decreases with increasing Ro. The intercept of the dashed lines on the vertical axis marks the ASDLs for different organic matter types. It was found that source rocks with type I (oil-prone), type II, and type III (gas-prone) of kerogen reach ASDLs at Ro of about 3.0%, 3.5% and 4.0%, respectively. This indicates that the oil-prone source rocks are more likely to reach the ASDL and stop generating and expelling hydrocarbons at a shallower burial depth under similar geological conditions.

Figure 3: Investigation of the influence of kerogen types on ASDLs represented by thermal maturity (Ro). From left to right, the hydrocarbon generation potential index of different types of source rocks were plotted versus Ro. a, the variation of hydrocarbon generation potential index ("S_1 + S_2"/TOC) with Ro for type I source rocks and identification of corresponding ASDL. b, the variation of hydrocarbon generation potential index ("S_1 + S_2"/TOC) with Ro for type II source rocks and identification of corresponding ASDL. c, the variation of hydrocarbon generation potential index ("S_1 + S_2"/TOC) with Ro for type III source rocks and identification of corresponding ASDL.

3.2.2 Heat Flow and Geothermal Gradient

ASDL is shallow in petroliferous basins with high heat flow and high geothermal gradient. The ASDLs in the six basins span from 5,400 m to 9,300 m as determined from hydrocarbon generation potential index (Fig. 4). The basins in western China are characterized with low heat flow and low geothermal gradient (1.5–2.8 °C/100 m) and thus have the deepest ASDLs ranging from 8,200 m to 9,300 m. The basins in eastern China are of high heat flow and high geothermal gradient (3.0–4.2 °C/100 m) and then have the shallowest ASDLs, ranging from 5,400 m to 5,900 m. The basins in central China are moderate in terms of heat flow and geothermal gradient, and the depths of ASDLs change from 6,600 m to 7,700 m. In addition, it was found that the burial depths corresponding to the HET vary similarly: lower burial depths relate to higher heat flow and higher geothermal gradient (Fig. 4).

In fact, the ASDL is also influenced by some other factors, such as tectonic uplift and the stratigraphic age of source rocks. As previous stated, the ASDL is mainly characterized by thermal maturity, and Ro=3.5% is regarded as general threshold for ASDL in common geological settings. However, the corresponding depth of ASDL for different source rock layers is highly variable. Due to the irreversible nature of the vitrinite reflectance (Hayes, 1991; Peters, 2018), the corresponding depth of ASDL for those older source rocks that was historically uplifted after reaching the ASDLs (Ro=3.5%) is relatively shallower compared with those younger source rocks. The Sichuan basin that experienced several stages of tectonic uplift in the geological history epitomizes the influence of these factors on ASDL. For example, the Ro of the upper Triassic source rock is about 1.0% at the depth of ~2000 m in the southern Sichuan basin (Zhu et al., 2016). At the same burial depth of southern Sichuan basin, however, the Ro of the lower Triassic source rock can reach about 2.0% (Zhu et al.,

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2016). Therefore, the tectonic uplift and the stratigraphic age of source rocks can have an influence on the corresponding depth of ASDL.

Figure 4: Variation characteristics of ASDLs with geothermal gradients (heat flows) in six representative basins in China. The ASDLs of different petroliferous basins in China are characterized by hydrocarbon generation potential index (represented by "$S_1 + S_2$"/TOC). The intercept of the dashed line, enveloping all the sample values, on the vertical axis marks the ASDL. From left to right, the heat flow (geothermal gradients) of each basin gradually increases, while the corresponding ASDL becomes shallower. a, Tarim Basin. b, Junggar Basin. c, Sichuan Basin. d, Ordos Basin. e, Bohai Bay Basin. f, Songliao Basin.

3.3 Quantitative prediction of ASDLs

According to the relationship of ASDLs with heat flows and kerogen types discovered with six basins in China, a quantitative model was established by statistical analyses using software Origin 2017 to predict ASDLs in different basins of the world using the available data. We analyzed the maximum depth of ASDLs as a function of heat flow with a linear model. The ASDL for each basin was represented by the average depth obtained from various indicators, and the heat flow used in the model was the average value of each basin (Table 1). We found a significant interaction between ASDLs and heat flows with coefficients larger than 0.9 (Fig. 5a). It was discovered that ASDLs for basins worldwide could range between 3,000 m and 16,000 m. Typically, ASDLs are less than 5,500 m in basins with high heat flow (>70 mW/m^2), and are larger than 9,000 m in basins with relatively low heat flow (<40 mW/m^2). Thus, the heat flow played an important role in variation of ASDLs, and the equation could be utilized to predict the ASDLs of basins from the documented heat flow. Given that the depth of ASDL is also influenced by organic matter type according to Fig. 3, we further analyzed the effects of organic matter type on ASDL by adding the hydrogen index, indicator of organic matter type, in the linear model. In our study, to quantize the influence of organic matter types on ASDLs, the type I, I–II, II, II–III and III kerogen corresponded to hydrogen index values of 600 mg HC/g TOC, 450 mg HC/g TOC, 525 mg HC/g TOC, 250 mg HC/g TOC and 125 mg HC/g TOC, respectively. The following equation was subsequently deduced showing the relationship between ASDLs and heat flows and kerogen types.

$$\mathrm{ASDL} = 16202 - 2.63 * \mathrm{HI} - 139.46 * \mathrm{HF}\,, \qquad (1)$$

where, ASDL is the active source rock depth limit, m; HI is the hydrogen index value of the major source rock in a basin, mg HC/g TOC; HF is the average heat flow value of a basin, mW/m^2.

We predicted the depth value of ASDL by using Eq. (1). The parameters such as heat flow and organic matter types for each basin were shown in Table 1. The result showed a strong correlation between the depth of ASDLs and measured depth of ASDLs, represented by the average values of the results obtained from different methods (Table 2), with a coefficient of

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0.9632 (Fig. 5b), indicating that the Eq. (1) is reliable. Such kind of understanding with practical implications provides the geological basis and boundary condition for the prediction of fossil fuels distribution and the evaluation of its potential.

Figure 5: The quantitative relationships among the ASDL, heat flow and kerogen type for petroliferous basins. a, relationship between heat flows and the maximum depths of ASDLs. b, a quantitative model between the depth of ASDL and its major geological factors, comparison of the predicted depths and measured depths of the ASDL for six representative basins in China.

3.4 ASDL controlling the vertical distribution of fossil fuel resources

Fossil fuel resources are formed from organic matter in the course of millions of years. They are currently the primary energy sources in the world, and can be utilized for various aspects in the industry. Oil and gas are the products during the evolution of organic matter, while coal is the residue of organic matter. On the other side, the ASDL is the critical condition or the dynamical boundary at which oil and gas expulsion ends. It controls the formation and distribution of favourable hydrocarbon reservoirs. Once the burial depth of organic matter exceeds the ASDL, the oil and gas could no longer be produced from the source rocks, and the coal which has been evolved to graphite would also lose their industrial value as fuel. Theoretically, the depth corresponding to ASDL represents the maximum depth of the formation and distribution of fossil fuels. According to Fig. 6, 97.7% of coal resources in China and 97.3% of recoverable coal reserves over the world are distributed above the ASDL corresponding to Ro of 4.0% (CCRR, 1996; CNACG, 2016; Conti et al., 2016). Therefore, ASDL controls the maximum depth of hydrocarbon reservoir distribution, including oil, gas and coal.

Figure 6: The variation characteristics of proved coal reserves with coal ranks in China and World. a, the proportion of proved coal reserves with different coal ranks in China (Data from CCRR, 1996; CNACG, 2016). The coal ranks are classified according to Chinese standard, and the coal accumulation area is shown in Fig. 1. b, the recoverable coal reserves with different coal ranks around the word (Data from Conti et al., 2016). The coal ranks are classified according to international standard. The proved coal reserves of anthracite C, B and A in China and world are projected according to their variation tendency.

This study also analysed the drilling results for 116,489 samples of target layers from 4,978 exploration wells of the six basins in China (Fig. 7). Exploration practices show that the reservoirs in the six basins are undoubtedly distributed above the ASDL, reflecting the control of ASDL on the formation and distribution of hydrocarbon reservoirs. The probability of drilling oil and gas reservoirs decreases with increasing burial depth, whereas the probability of drilling dry layers increases. At some depth, the probability of drilling oil or gas reservoirs decreases to zero, this depth is regarded as the Hydrocarbon Reservoir Depth Limit (HRDL). The HRDLs of the six basins are marked in Fig. 7 as yellow dots and connected by a dashed red line. The ASDLs deduced from ("S_1 + S_2")/TOC (Table 2) are also marked in Fig. 7 and connected with a solid blue line.

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Meanwhile, according to the vertical distribution characteristics of proved hydrocarbon reserves, it is discovered that all proved hydrocarbon reserves in the six representative basins are controlled by HRDL which is above ASDL (Fig. 7; Fig. S6). This means a basin's HRDL is controlled by its ASDL and should always be above the ASDL. The currently discovered natural gas hydrate over the world are also distributed above the ASDL with corresponding Ro < 4.0% (Dai et al., 2017). We further extended the research to 52,926 reservoirs in 1,186 basins over the world recorded in IHS (2010). HRDL for each basin was derived from the actual reservoir depth data in IHS (2010) using the same way as described in the previous paragraph (Fig. 7) and the results were shown in Fig. 8. ASDL for each basin was assumed to be at Ro of 3.5%, and the corresponding depth can be calculated from the documented heat flow of that basin. We found that HRDL (represented as depth) is universally above ASDL for all the basins.

Figure 7: Hydrocarbon drilling results in the six representative petroliferous basins of China to show their relationships with the ASDLs and the HRDLs. The results include 116,489 samples of target layers from 4,978 exploration wells in China. The intercept of the blue dashed line, enveloping all the sample values, on the vertical line corresponding to 2% of porosity marks the HRDL. The ASDL of each basin shown in this figure is represented by the value obtained from hydrocarbon generation potential index ("S_1 + S_2"/TOC) of each basin. From left to right: a, Tarim Basin. b, Junggar Basin. c, Sichuan Basin. d, Ordos Basin .e, Bohai Bay Basin. f, Songliao Basin. It is found that HRDLs are always above the ASDLs.

Figure 8: The vertical distribution characteristics of numbers of discovered hydrocarbon reservoirs and their relationships with ASDLs and HRDLs in the worldwide 1,186 petroliferous basins. a, summation of 1,186 petroliferous basins. b, lower heat flow basin (<25 mW/m^2). c, relative lower heat flow basin (25–40 mW/ m^2). d, relative high heat flow basin (40–55 mW/ m^2). e, high heat flow basin (55–70 mW/ m^2). HRDL represents the hydrocarbon reservoir depth limit. The intercept of the green dashed line, enveloping all the sample values, on the vertical axis marks the HRDL. The ASDL, shown in this figure, of each kind of basin with different heat flow is predicted by using the equation shown in Fig. 5.

Hydrocarbon is generally classified in two big categories as natural gas and liquid petroleum, which have distinct physical properties. By definition, ASDL marks the end of generation of any hydrocarbon from source rocks. This concept can be modified to incorporate the types of hydrocarbons, such as ASDL for gas and ASDL for oil. ASDL for oil indicates that the source rocks can no longer generate oil and is named oil supply limit, while ASDL for gas indicates that the source rocks can no longer generate gas and is named gas supply limit. The hydrocarbon components are mainly liquid oil and gaseous hydrocarbons when the thermal maturity is low. The gaseous hydrocarbons become the dominant components with nearly no liquid oil when the thermal maturity is high. Therefore, theoretically speaking, the burial depth and thermal maturity corresponding to ASDL for oil should be lower that of ASDL for gas. To investigate the ASDLs for different fluids, the high temperature (room temperature to 600 °C) and high pressure (50 MPa) pyrolysis simulation experiments were conducted on immature or low-mature kerogen sampled from Junggar Basin in a closed system. According to the experiment

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results, source rocks reached oil supply limit at Ro of about 2.0% (Fig. 9), and the same source rocks reached gas supply limit at Ro of 3.0 to 4.0%, which is also the overall ASDL.

Figure 9: Investigation of ASDLs for different hydrocarbon types using the high temperature and high pressure reactor. The experiments were conducted on kerogen samples from Junggar Basin in a closed system. a, the variation of oil production rate with Ro and identification of oil supply limit (ASDL for oil). b, the variation of gas production rate with Ro and identification of gas supply limit (ASDL for gas) which varies from Ro of 3.0% to Ro of 4.0%.

Besides, Pang et al. (2005) proposed the concept of hydrocarbon expulsion threshold, which marks the starting point of source rocks expelling hydrocarbons at certain depth. The HET, oil supply limit and gas supply limit divide a basin into three regions along the vertical direction, and they control the types of hydrocarbon reservoirs and their distributions (Fig. 10). The top area (blue area in Fig. 10) is favourable for hydrocarbons migrating upward to form conventional reservoirs in traps, and the source rocks in this area do not yet expel hydrocarbons. The middle area (pink area in Fig. 10) is favourable for source rocks to generate, expel and retain hydrocarbons to form various kinds of oil reservoirs, and this area also supplies hydrocarbons that migrate into the top area. The bottom area (yellow area in Fig. 10) is favourable for source rocks to generate, expel and retain natural gas to form mainly unconventional resources. Figure. 10 includes a series of low-heat-flow to high-heat-flow basins in the world and illustrates the effect of heat flow on HET and ASDLs. The characteristics for hydrocarbon generation and reservoirs distribution differ in basins due to their geological conditions and tectonic settings, the controlling of ASDLs on them are indispensable and can be identified (SRCOGR, 2009).

Figure 10: The controlling pattern of ASDLs on the formation and distribution of hydrocarbon reservoirs in petroliferous basins. The top blue area is favourable for the formation and distribution of conventional oil and gas resources migrated from source rocks below this area; The middle pink area is favourable for oil and gas generation, migration, and accumulation from source rocks in this area; The bottom yellow area is favourable for nature gas generation, migration, and accumulation from source rocks in this area.

4. Conclusions

(1) ASDLs, the maximum burial depth for source rocks to generate and expel oil and gas due to exhausting of hydrocarbon generation potentials, commonly exist in petroliferous basins. The thermal maturity of 3.5% can be regarded as the ASRL in general geological conditions.

(2) The ASRLs of all basins over the world vary from 3,000 m to 16,000 m, and the variation is mainly influenced by different heat flows and different organic matter types. As the heat flow gets lower and the organic matter gets more gas-prone, the ASDLs become deeper.

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(3) All kinds of reservoirs, including coal, conventional hydrocarbons and unconventional hydrocarbons, in petroliferous basins are formed and distributed above the ASDLs. The petroliferous basins could be vertically divided into three regions by the HET, oil supply limit and gas supply limit, which are favourable for different types of hydrocarbons accumulation.

Data availability

The datasets can be accessed through https://doi.pangaea.de/10.1594/PANGAEA.900865 (Pang et al., 2019).

Author contributions

Xiongqi Pang proposed the concept of ASDL, designed the study and led the writing of the manuscript in close collaboration with Kun Zhang and Junqing Chen. The data used in this study was collected by Youwei Wang and Boyuan Li, respectively. Chengzao Jia helped collect the data and explained the significance of ASDL. Kun Zhang investigated the influence of geothermal gradient on ASDL. Maowen Li studied the influence of organic matter type on ASDL. Junwen Peng illustrated the mechanism of depletion of hydrocarbon generation potential. All authors reviewed and approved the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1. Geological and geochemical characteristics of the main source rocks from the six representative petroliferous basins in China

Basin location	Basin name	Basic features of representative basins				Features of main source rocks			
		Basin type	Basin area (10^4 km^2)/ maximum depth (m)	Heat flow (mW/m^2)/ geothermal gradient (°C/100 m)	National Ranking of reserves/ resources	Age and lithology	Organic matter abundance (TOC, %)	Organic matter type	Maximum measured maturity (Ro, %)
Western China	Tarim Basin	Complex superimposed basin	53/ 9100	43.0/ 2.00	5/2	Cambrian–Ordovician Carbonate	0.2–5.0	I–II	3.7*
	Junggar Basin	Complex superimposed basin	38/ 8900	45.0/ 2.30	4/5	Permian Shale	0.5–3.5	I–II	2.5
Central China	Sichuan Basin	Superimposed basin	26/ 7800	58.3/ 2.35	6/6	Triassic Shale	1.0–3.0	II–III	3.2
	Ordos Basin	Superimposed basin	37/ 6100	62.9/ 2.75	3/4	Carboniferous–Permian Coal strata	2.0–6.5	II–III	2.8
Eastern China	Bohai Bay Basin	Fault Depression basin	20/ 5800	64.8/ 3.20	1/1	Paleogene Shale	1.0–4.0	I–II	2.7
	Songliao Basin	Rift-fault basin	26/ 5400	69.0/ 4.00	2/3	Jurassic–Cretaceous Shale	1.0–4.0	I–II	3.6

* Ro =0.618*Ro^B +0.40, Ro^B is solid bitumen reflectance,%.

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Table 2 Comparison of active source rock depth limits in the six petroliferous basins of China

Research methods and related indicators for identifying ASDLs		The maximum burial depth (D, m) and thermal maturity (Ro, %) corresponding to Active Source Rock Depth Limits						
		Tarim Basin	Junggar Basin	Sichuan Basin	Ordos Basin	Bohai bay Basin	Songliao Basin	The average values for six basins
The variation of element composition	H/C	8970/3.5	8350/3.2	–	–	5800/3.5	5280/3.6	7100/3.4
	O/C	9050/3.6	8450/3.2	–	–	5740/3.4	5280/3.6	7130/3.4
The variation of residual hydrocarbon	"A"/TOC	9050/3.6	7850/3.0	7540/3.6	6450/3.3	5560/3.1	5330/3.7	6963/3.4
	"S_1"/TOC	9290/3.8	7960/3.0	7780/3.8	6500/3.4	5490/3.2	5400/3.9	7070/3.5
The variation of hydrocarbon generation and expulsion	"S_1+S_2"/TOC	9300/3.8	8200/3.0	7700/3.8	6600/3.4	5900/3.3	5400/3.9	7183/3.5
	Ve	9210/3.8	8200/3.0	7660/3.7	6520/3.4	5700/3.3	5500/4.0	7115/3.5
The average values obtained from different methods in each basin		9145/3.7	8168/3.1	7670/3.7	6518/3.4	5698/3.3	5348/3.8	7094/3.5
The data used for identifying ASDLs (sample number/well number)		2063/79	5353/351	460/27	1329/149	1193/69	3236/611	Total: 13634/1286

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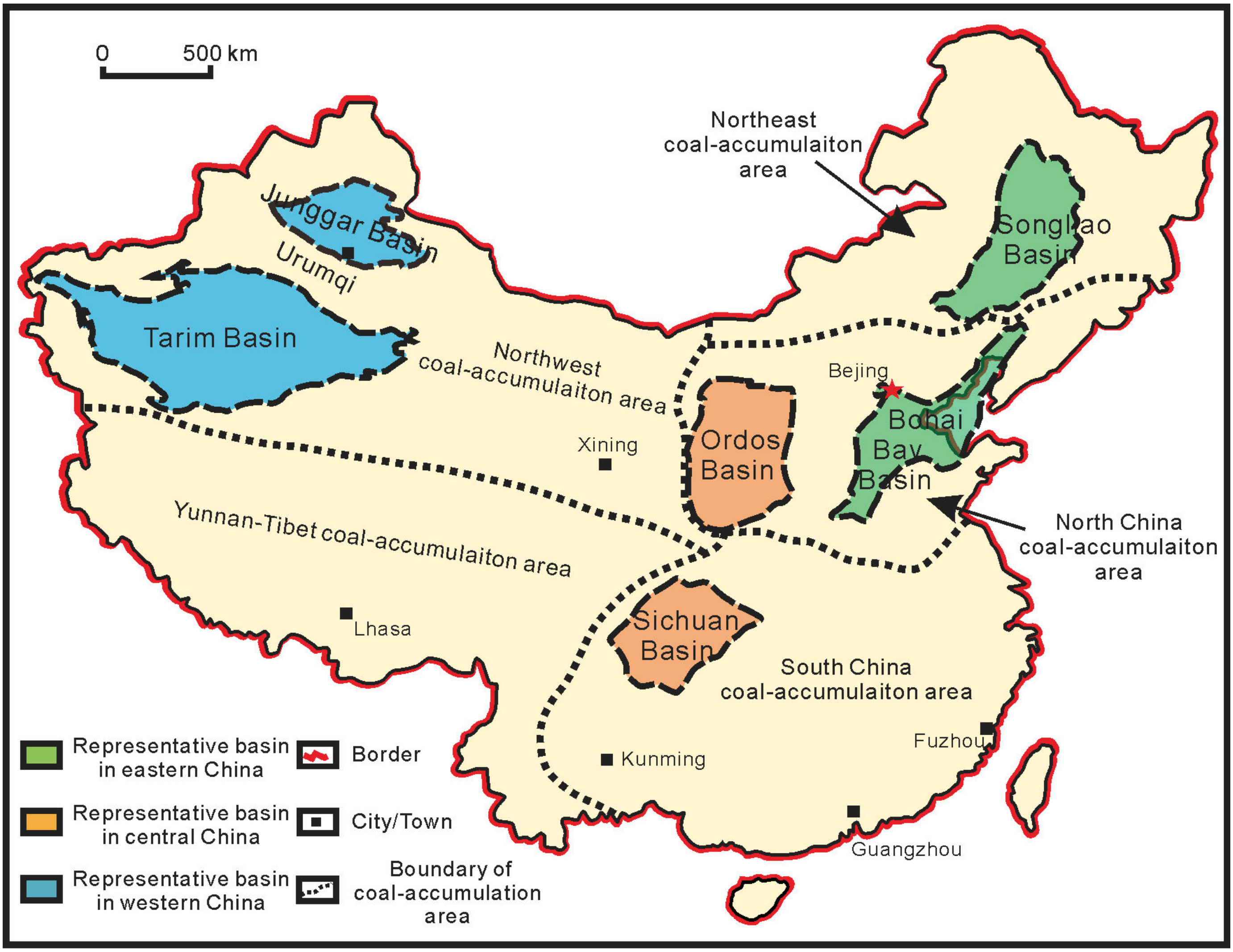

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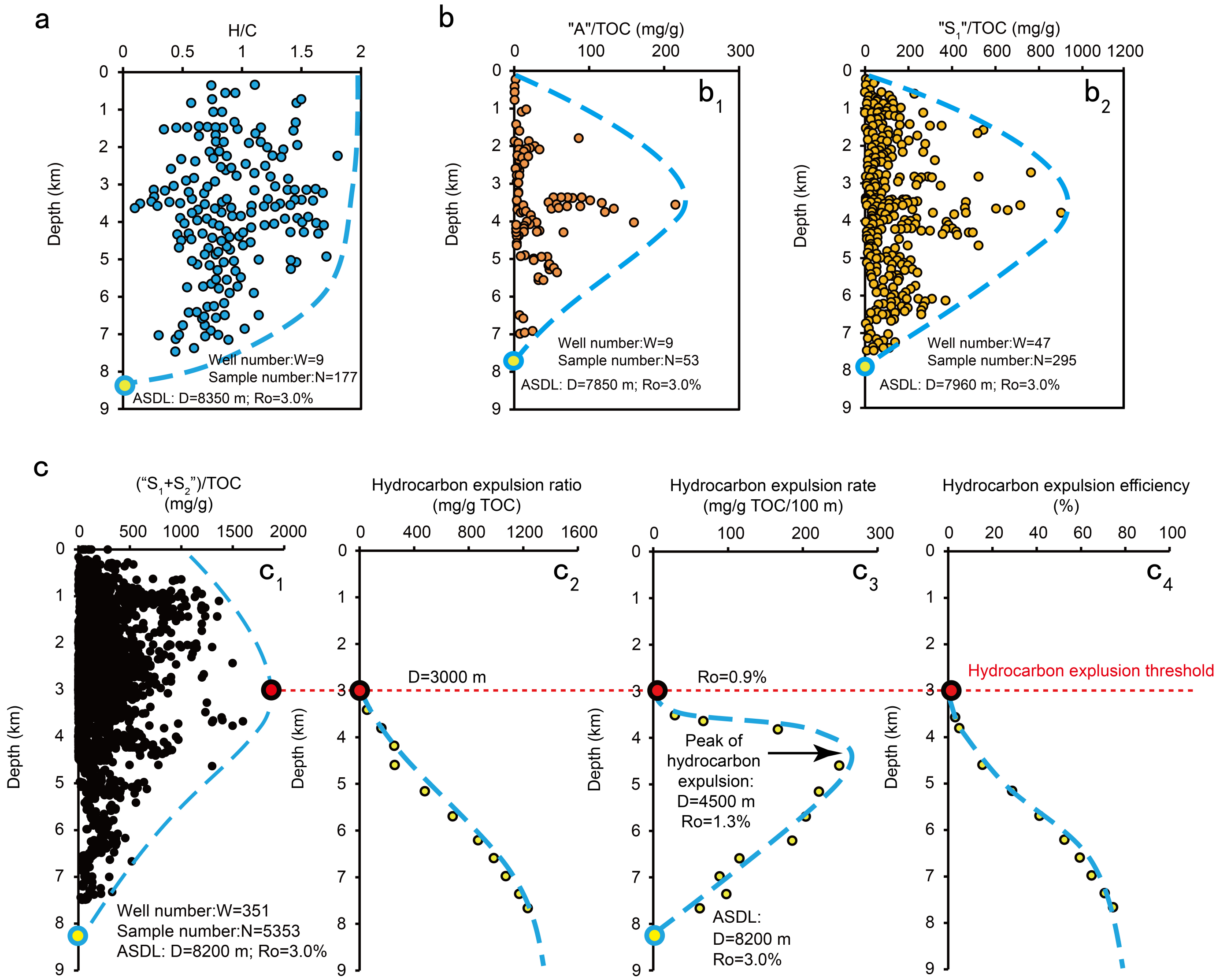

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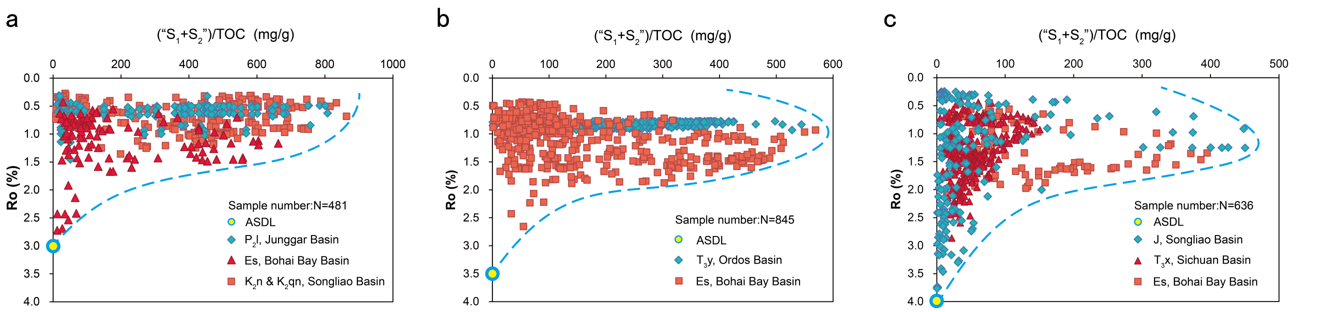

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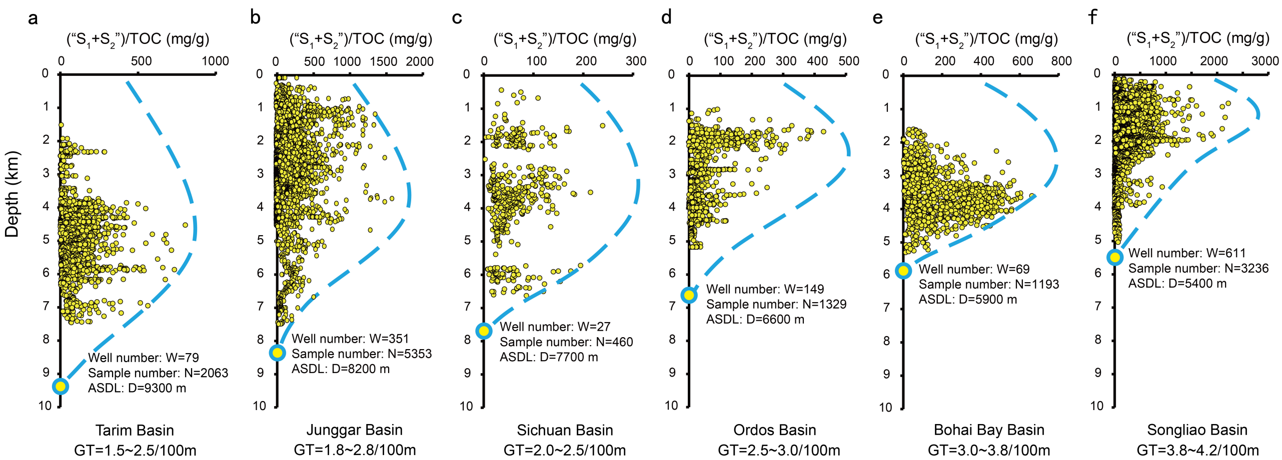

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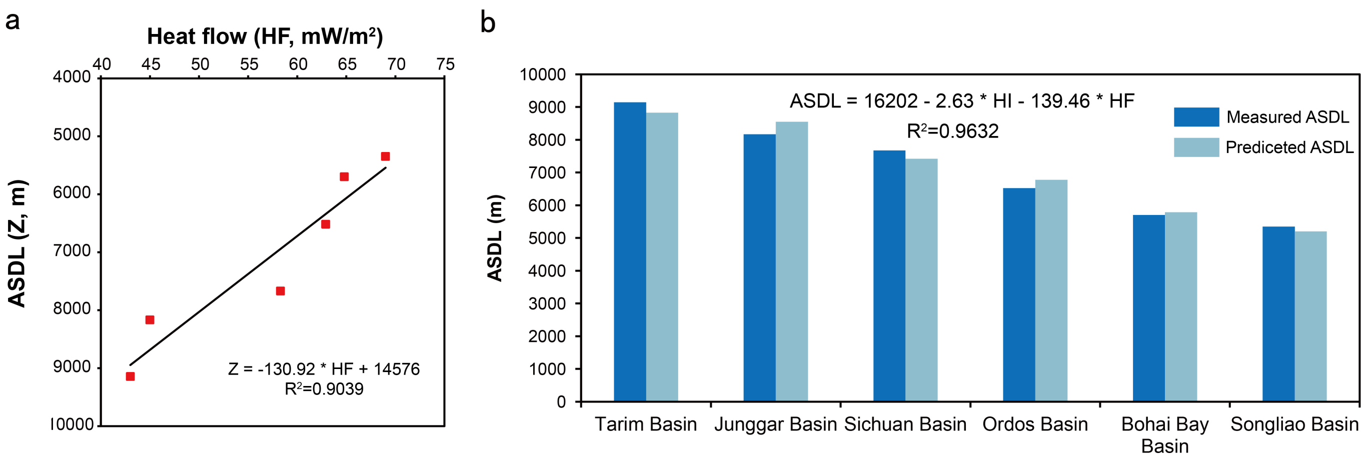

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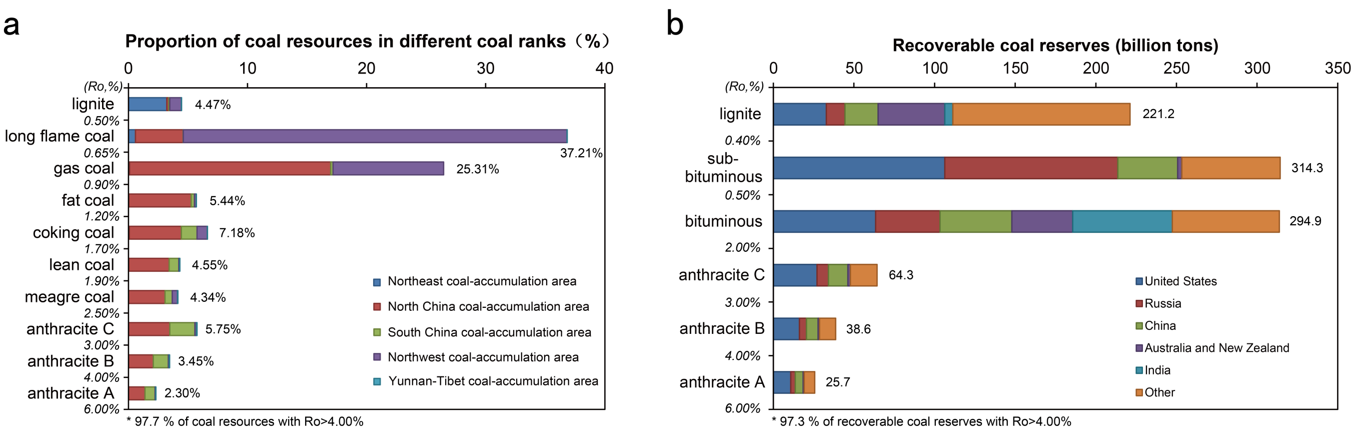

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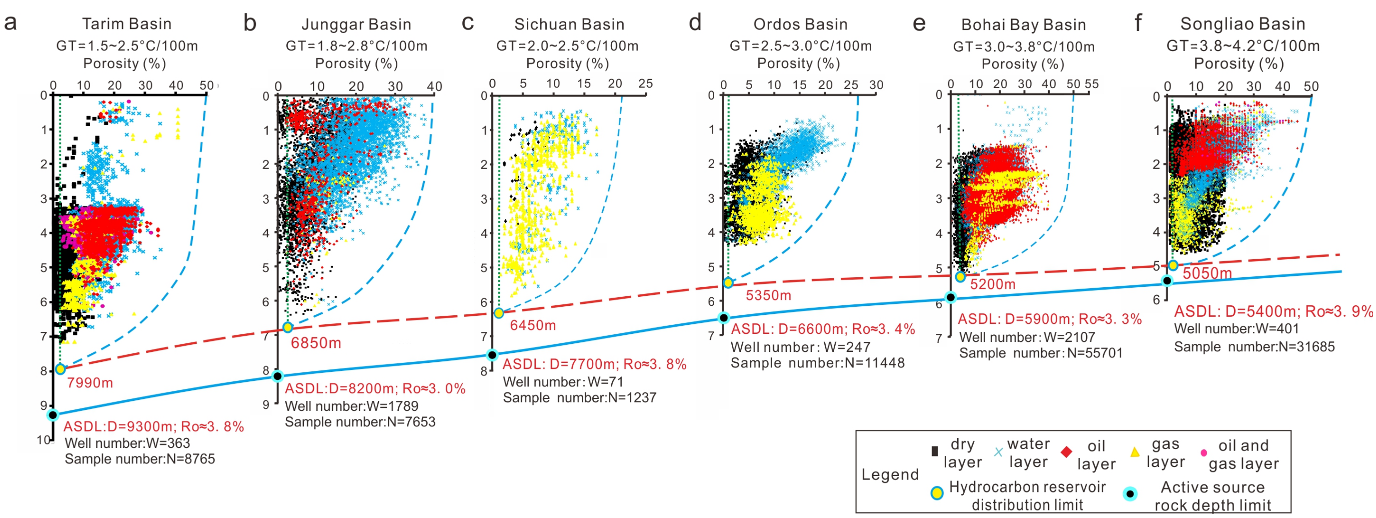

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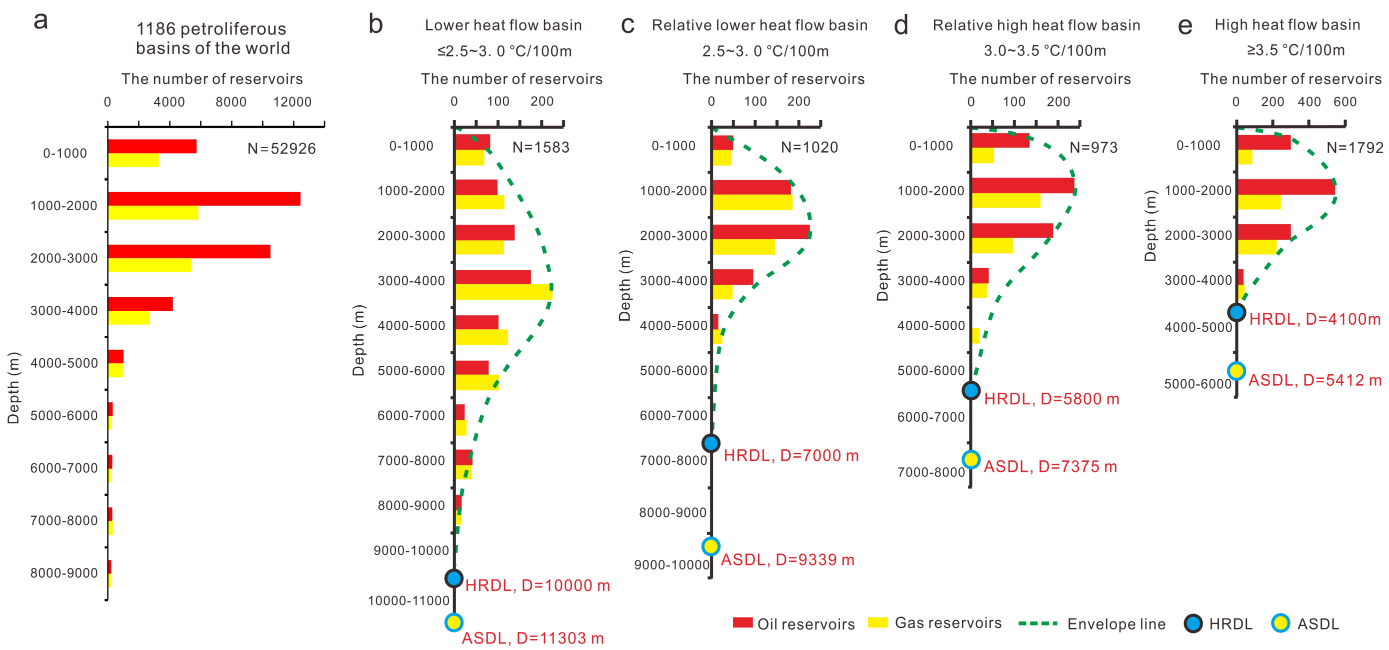

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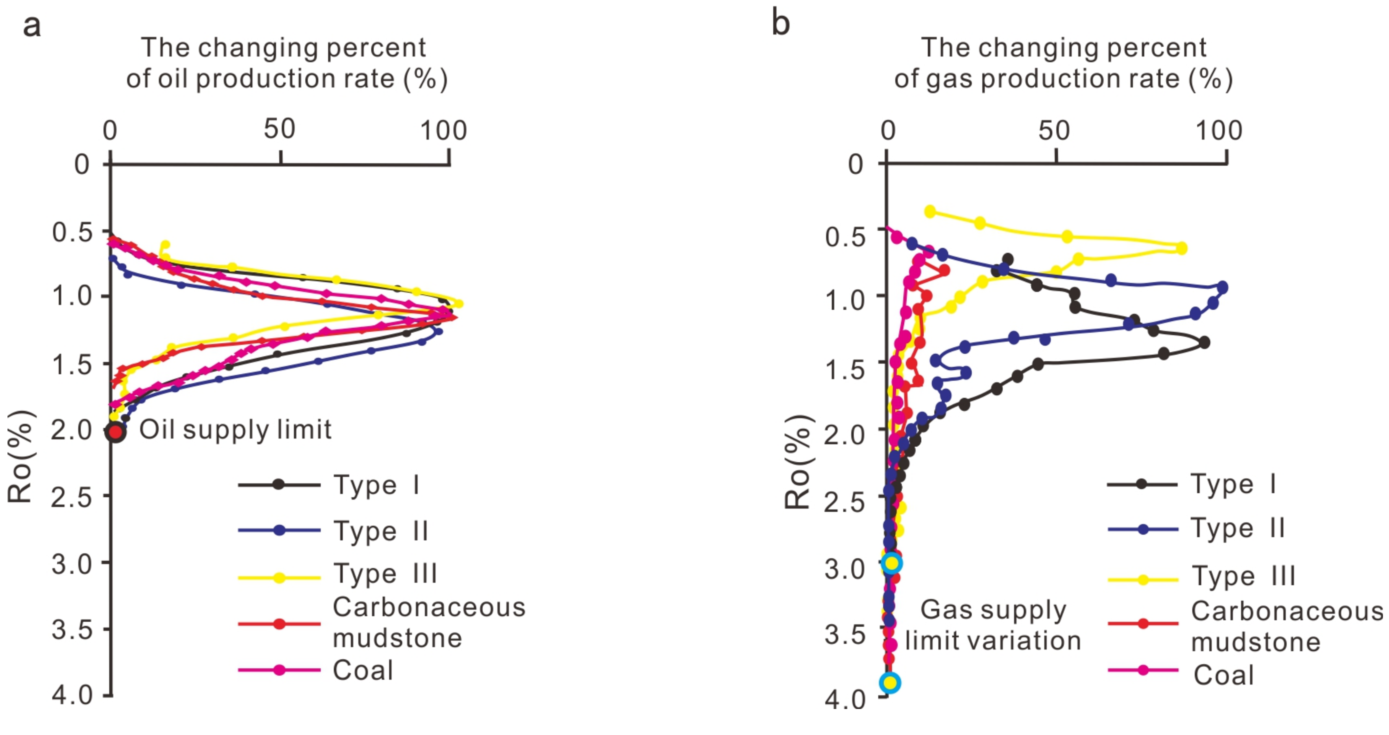

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