Dear Editors and Reviewers,

We are deeply grateful for the editorial board's consideration of our manuscript, and we would also like to express our deep appreciation to reviewers for two referee comments and four short comments. Their constructive suggestions and insightful comments really help us improve the readability, quality, and rigour of the manuscript. We have revised the manuscript carefully following the suggestions. In this response, we have clarified what we have done to tackle the issues proposed by the reviewers. For clarity's sake, the comments are in **bold** type, and the responses including additional works that have been implemented into the manuscript are in normal type with blue colour.

Referee Comment #1 by György Pogácsás

General Comments: The overall structure of the Xiongqi Pang et al "Active Source-rock Depth Limit and Its Controlling on the Formation and Occurrence of Fossil Fuel Resources" article is fairly well structured and clear. The length of the paper is appropriate. The figures and tables are correct and good quality. The article is implemented by the Supplement and by the Data sets. The colour diagrams on both the figures of the article and on the figures of the Supplement are really beautiful and very informative. The Supplement figures (Fig. S1-Fig. S5) illustrate the identification of the Active Source Rock Depth Limit (ASDL) within the Tarim Basin, Sichuan Basin, Ordos Basin, Bohai Bay Basin, and Songliao Basin using different indicators. Supplement Fig. S6. illustrates the distribution of proven hydrocarbon reserves versus depth (and their relationships with ASDLs and HADLs) within the Tarim Basin, Junggar Basin, Sichuan Basin, Ordos Basin, Bohai Bay Basin, and Songliao Basin.

(1) The article and the data sets are more or less consistent. The excel spreadsheets of the Datasets (Fig.2.xlsx-Fig.9.xlsx) are strictly connected to the figures of the article as follows: Fig.2.xlsx to Fig.2; Fig.3.xlsx to Fig.3; Fig.4.xlsx to Fig.4; Fig.5.xlsx to Fig.5; Fig.6.xlsx to Fig.6; Fig.7.xlsx to Fig.7; Fig.8.xlsx to Fig.8; Fig.9.xlsx to Fig.9; whereas Fig.10 is connected both to Fig.8.xlsx and to the tables of the paper (Table 1. and Table 2). The Supplement figures referring to the Tarim Basin, Sichuan Basin, Ordos Basin, Bohai Bay Basin, and Songliao Basin, unfortunately are not corroborated by excel spreadsheets containing the data sets which were used for the construction of Fig. S1.-Fig. S5. Only in the case of the Junggar Basin figure (Fig.2) are available the excel spreadsheets

(Fig.2.xlsx) at (https://doi.pangaea.de/10.1594/PANGAEA.900865) containing the geochemical data which were used to construct the diagrams on Fig.2.

Response: Thanks for your suggestion. We have supplemented the geochemical datasets that can be utilized to construct the figures of Fig.S1-Fig.S5. It should be clarified that during the process of organizing the uploaded data, we found serious errors in previously supplemented figures and we are very sorry for that. In the subfigure (a) and (b) of Fig.S1-Fig.S5, the ordinate should be the thermal maturity, i.e. Ro, that the depth. We have corrected this in the newly supplemented figures, and have also uploaded the relevant data. Ro is chosen because it is closely related to the ASDL, and hydrocarbon generation and expulsion. Furthermore, according to the reviewers' suggestion, the original data was further proofread during the process of organizing the data, and the number of data points has changed slightly due to the screening of outliers. But the overall trends have not been changed.

Changes: We have supplemented the geochemical datasets that can utilized to construct the figures of Fig.S1-Fig.S5. The supplementary files are also updated during the revision. Please find the updated datasets and figures in the attached supplementary file.

(2) The related Data sets at https://doi.pangaea.de/10.1594/PANGAEA.900865 contain an enormous number of geochemical data but the structure of the data sets excel spreadsheets (Fig.xlsx) does not seems to be the luckiest one. Although the different geochemical parameters of a source rock samples are strongly connected, the geochemical data cube of the article is separated and segmented: H/C versus depth, S1/TOC versus depth, A/TOC versus depth, (S1+S2)/TOC versus Ro, (S1+S2)/TOC versus depth etc. It does not help very much to understand the petroleum generation in the six representative Chinese basins.

Response: The primary purpose for constructing such kind of structure is for the convenience of the scientific and industrial community to reproduce the figures in the manuscript quickly and to reutilize these data efficiently. The reviewer, however, did pinpoint an important issue we have ignored, and therefore thank you very much for your comment. For the data that have been uploaded to the PANGAEA, it may be difficult to change the structure of these data, but as for the new data, we have followed the reviewer's suggestion to put every basin's geochemical data (i.e. H/C versus depth, S1/TOC versus depth, A/TOC versus depth, (S1+S2)/TOC versus Ro, (S1+S2)/TOC versus depth) in a same excel sheet, so as to correlate the data with petroleum generation more closely.

Changes: We have followed the reviewer's suggestion to put every basin's geochemical data in a same excel sheet. Please find the datasets in the attached supplementary file.

(3) To provide additional references concerning the petroleum systems of the Tarim Basin, Junggar Basin, Sichuan Basin, Ordos Basin, Bohai Bay Basin, Songliao Basin is strongly recommended. The article is focusing on questions related to depth limit of petroleum generation and occurrence. Geochemical data are definitely needed to answer these kinds of questions and the paper itself seems to be appropriate to support the publication of the enclosed enormous geochemical data sets. Although question may arise concerning the need to use additional type (geology, geophysics etc.) of data as well to give even more precise answer concerning depth limit of petroleum generation within sedimentary basins.

Response: Thank you very much for your suggestion. The additional references, especially for geology and geophysics, with respect to petroleum systems of the six representative basins have been provided in the revised manuscript.

Changes: In the section 3.1, we have briefly introduced the petroleum system of the Junggar basin and provided the references regarding the petroleum systems of other five basins. The detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

The references added are listed here:

1. Wang, S., He, L., & Wang, J.: Thermal regime and petroleum systems in Junggar Basin, northwest China. Physics of the Earth and Planetary Interiors, 126(3-4), 237-248, doi:10.1016/S0031-9201(01)00258-8, 2001.

2. Cao, J., Zhang, Y., Hu, W., Yao, S., Wang, X., Zhang, Y., & Tang, Y.: The Permian hybrid petroleum system in the northwest margin of the Junggar Basin, northwest China. Marine and Petroleum Geology, 22(3), 331-349, doi:10.1016/j.marpetgeo.2005.01.005, 2005.

3. Chen, Z., Zha, M., Liu, K., Zhang, Y., Yang, D., Tang, Y., Tang, Y., Wu, K., & Chen,

Y.: Origin and accumulation mechanisms of petroleum in the Carboniferous volcanic rocks of the Kebai Fault zone, Western Junggar Basin, China. Journal of Asian Earth Sciences, 127, 170-196, doi:10.1016/j.jseaes.2016.06.002, 2016.

4. Wang, Y., Yang, R., Song, M., Lenhardt, N., Wang, X., Zhang, X., Yang, S., Wang, J., & Cao, H.: Characteristics, controls and geological models of hydrocarbon accumulation in the Carboniferous volcanic reservoirs of the Chunfeng Oilfield, Junggar Basin, northwestern China. Marine and Petroleum Geology, 94, 65-79, doi:10.1016/j.marpetgeo.2018.04.001, 2018.

5. Zhou, Y., & Littke, R.: Numerical simulation of the thermal maturation, oil generation and migration in the Songliao Basin, Northeastern China. Marine and Petroleum Geology, 16(8), 771-792, doi:10.1016/S0264-8172(99)00043-4, 1999.

6. Xiao, X. M., Zhao, B. Q., Thu, Z. L., Song, Z. G., & Wilkins, R. W. T.: Upper Paleozoic petroleum system, Ordos Basin, China. Marine and Petroleum Geology, 22(8), 945-963, doi:10.1016/j.marpetgeo.2005.04.001, 2005.

7. Wu, S. X., Jin, Z. J., Tang, L. J., & Bai, Z. R.: Characteristics of Triassic petroleum systems in the Longmenshan foreland basin, Sichuan province, China. Acta Geologica Sinica - English Edition, 82(3), 554-561, doi:10.1111/j.1755-6724.2008.tb00606.x, 2008.

8. Ping, H., Chen, H., & Jia, G.: Petroleum accumulation in the deeply buried reservoirs in the northern Dongying Depression, Bohai Bay Basin, China: New insights from fluid inclusions, natural gas geochemistry, and 1-D basin modeling. Marine and Petroleum Geology, 80, 70-93, doi:10.1016/j.marpetgeo.2016.11.023, 2017.

9. Zhu, G., Cao, Y., Yan, L., Yang, H., Sun, C., Zhang, Z., Li, T., & Chen, Y.: Potential and favorable areas of petroleum exploration of ultra-deep marine strata more than 8000 m deep in the Tarim Basin, Northwest China. Journal of Natural Gas Geoscience, 3(6), 321-337, doi:10.1016/j.jnggs.2018.12.002, 2018.

(4) According to the article the Active Source Rock Depth Limit (ASDL) was studied basically by two more or less independent methods. The first one was a graphic method, constructing diagrams (H/C versus depth; A/TOC versus depth; S1/TOC versus depth; (S1 + S2)/TOC etc.) and "drawing dashed curve to envelope all the sample values and assuming the intercept of the dashed line on the vertical axis marks the ASDL". The second method applied linear equation as follows: ASDL = 16202 - 2.63 x HI + 139.46 x HF; "where, ASDL is the active source rock depth limit; HI is the hydrogen index value of the major source rock in a basin; HF is the average heat flow value of the given basin". In the case of

the graphic method considerable uncertainty is related to the lack of ultra-deep wells why the drilled boreholes were terminated by some kilometres above the ASDL. In the case of the ASDL = 16202 - 2.63 x HI + 139.46 x HF equation the main uncertainty is related to the facts that heat flow values of the sedimentary basins are geologic time dependent and the thermal maturation is not the only function of HI and HF value, but it depends on other factors (time etc.) as well. Oil companies and research institutes all over the world apply sophisticated methods for modelling the source rock maturation versus time and versus depth, besides geochemical data using subsidence history reconstructions, deposition history models, compaction history models, thermal history calculations and so on. It is assumed comparison of the graphic method based and the linear equation (ASDL = 16202 - 2.63 x HI + 139.46 x HF) based results of the article with results of source rock maturation versus depth and time modelling would provide even more precise expectations concerning the depth limit of the ASDL within the studied basins.

Response: Thank you very much for your suggestion. We totally agree with the reviewer that these uncertainties may play an important role in affecting the depth limit of the ASDL. Therefore, we have modified the manuscript from the following aspects. For the first case that uncertainties may be caused by the lack of datasets from ultra-deep wells, the ASDL can be identified by extrapolation according to the variation regularity of these data with depth, and such kind of regularity is derived from the actual data from different basins. For the second case that uncertainties may be brought in by the quantitative equation, we have re-written the section 3.3 in the revised manuscript that the proposed equation is only used to elucidate that there exists a relationship between the ASDL and the heat flow and organic matter type. This is because, as the reviewer suggested, the influence factors of the ASDL are not fully incorporated into the equation. We have already mentioned in the manuscript that the ASDL is not only influenced by the heat flow and organic matter type, but also influenced by the stratigraphic age and tectonic uplift. However, to set up the equation with four independent variables by using our database with only 6 basins is difficult and impossible. Therefore, we have supposed in the revised manuscript that the proposed equation cannot utilized to predict precisely the ASDL of source rocks in other basins except the six representative basins of China, especially for basins out of China. On the other hand, basin modelling and some other integrated analysis methods, just as the reviewer suggested, should be applied if readers want to decide the depth limit of ASDL which should be correspondence to the criteria provided by our study (i.e. Ro=3.5% ± 0.5%).

Changes: We have added relevant content in section 3.1 and re-written section 3.3 according to the above response, and the detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

(5) Careful English language revision of the article by a native English college is strongly recommended.

Response: Thanks for your suggestion. We have modified the manuscript with the help of a native English researcher.

Changes: The manuscript has been polished by a native English researcher, and please find the marked-up manuscript at the end of this response to see the detailed revisions.

Referee Comment #2 by Ludden John

General Comments: This manuscript is a useful contribution of data from numerous oil and gas wells in China and a world-wide compilation. It provides very useful data that is on-line in the PANGEA data-base. I would expect these data to be used by a number of users both from academia and industry and this is a good example of open data.

(1) The only thing I struggle with is the static view of basins in these models. The oil and gas community model the source rocks as expelling gas and oil simply due to subsidence and compaction - as in Figure 9. This is largely because the oil and gas producers are mainly interested in the reservoir rather than the source - so they focus on the trapping process. Here the authors attempt to define limits for expulsion and these vary with heat flow of the basin as one would expect. However, there are fluxes of fluids, water rich and saline, traversing these basins and the role of these in dissolving organic matter and redistributing it has largely been ignored. I refer the authors to a recent paper which I was associated with in which we show that Pb- in oil comes from older and clearly deeper sources and is a mixture of components Lead isotopes as tracers of crude oil migration within deep crustal fluid systems Earth and Planetary Science Letters, Volume 525, 1 November 2019, Article 115747.

Response: Thanks for your suggestion. It is true that source rocks can expel hydrocarbons as the consequence of thermal maturation with increasing depth, and there are a variety of software to model such kind of process. It is hard to say, however, that the oil and gas companies are mainly interested in the reservoirs rather than the source rocks. Conversely, these companies are paying more attention to the source rocks than ever before, which may be induced by the U.S. shale revolution to a large extent. On the other hand, we agree with the reviewer that the fluid fluxes have influences on the generation, preservation and redistribution of organic matter in source rock, and then have influences on its ASDL. Therefore, we have discussed the relevant problems and added relative references in the revised manuscript.

Changes: According to the reviewer's suggestion, we have added created a new section 3.2.3 to discuss the influence of deep thermal fluids and overpressure on the ASDL. The detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

The references added are listed here:

1. McTavish, R. A.: The role of overpressure in the retardation of organic matter maturation. Journal of Petroleum Geology, 21(2), 153-186, doi:10.1111/j.1747-5457.1998.tb00652.x, 1998.

2. Hao, F., Zou, H., Gong, Z., Yang, S., & Zeng, Z.: Hierarchies of overpressure retardation of organic matter maturation: Case studies from petroleum basins in China. AAPG bulletin, 91(10), 1467-1498, doi:10.1306/05210705161, 2007.

3. Fetter, N., Blichert-Toft, J., Ludden, J., Lepland, A., Borque, J. S., Greenhalgh, E., Garcia, B., Edwards, D., Télouk, P., & Albarède, F. (2019). Lead isotopes as tracers of crude oil migration within deep crustal fluid systems. Earth and Planetary Science Letters, 525, 115747.

4. Rullkötter, J., Leythaeuser, D., Horsfield, B., Littke, R., Mann, U., Müller, P. J., Schaefer, R.G., Schenk, H.-J., Schwochau, K., & Witte, E. G.: Organic matter maturation under the influence of a deep intrusive heat source: a natural experiment for quantitation of hydrocarbon generation and expulsion from a petroleum source rock (Toarcian shale, northern Germany). Organic Geochemistry, 13(4-6), 847-856, doi:10.1016/0146-6380(88)90237-9, 1988.

5. Zhu, D., Liu, Q., Jin, Z., Meng, Q., & Hu, W.: Effects of deep fluids on hydrocarbon generation and accumulation in Chinese petroliferous basins. Acta Geologica Sinica ‐ English Edition, 91(1), 301-319, doi:10.1111/1755-6724.13079, 2017.

(2) There is some minor grammatical structuring that the authors should ensure for clarity in particular in the section - last paragraph on characteristics of ASDL.

Response: Thank you for the suggestion on language improving. We have modified the manuscript with the help of a native English researcher.

Changes: The manuscript has been polished by a native English researcher, and please find the marked-up manuscript at the end of this response to see the detailed revisions.

Short Comment #1 by Shuang Xiao

General Comments: I believe this is a very nice study. This manuscript proposed a new model and workflow to quantitative predict the depth limit of the fossil fuel resources in sedimentary basins, which has a wide implication in nowadays petroleum industry. Abundant oil exploration and production data from PetroChina and Sinopec were integrated in this study to illustrate their model. But I still have some comments and suggestions here:

(1) Does the laboratory workflows for all these geochemical data as shown in figures 2, 3, and 4 are the same? Is there any deviation for different these data caused by different laboratory workflows?

Response: Thanks for your comment. All these geochemical data shown in Figures 2, 3, 4 are obtained following the same workflows which are in accordance with Chinese Petroleum and Natural Gas Industry Standard of P.R. China. We admit that there may be deviations due to the experimental errors, but the deviations of these data are within the controllable range since the workflows strictly follow a suit of standards.

Changes: According to the above response to the reviewer, there is no change in the revised manuscript related to this comment.

(2) How does the dashed envelope line be established in figures 2, 3, and 4? It's formed by handwriting or any professional software? It seems that some of these dashed envelope lines are not that well fit with the geochemical data.

Response: Thanks for your comment. As described in the manuscript, the envelope line is drawn by including all sample values. Instead of randomly drawing, the envelope line drawn by handwriting on the model of numerous previous studies investigating the changing trend of hydrocarbon generation potential index and actual geological data.

Changes: We have added a part of content in section 3.1 clarifying the determination of envelope lines, and the detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

(3) How to preclude these outlier geochemical data? Is it possible that some outlier geochemical data (such as fig. 2b) are caused by detection deviation?

Response: Thanks for your comment. The outlier is a data that differs significantly from other observations, and according to this trait, some outlier data have already been discarded during the compilation of these geochemical data. However, in Fig. 2b1, for example, the highest value is not significantly different from the others. On the other hand, even if we exclude those "outlier" data as supposed by Shuang Xiao, a clear trend still stands with remaining data and the turning point corresponding to hydrocarbon expulsion threshold does not change. Therefore, we argue that these data are not outliers.

Changes: According to the above response to the reviewer, there is no change in the revised manuscript related to this comment.

Short Comment #2 by Jie Zhou

General Comments: As the conventional reservoirs have been mostly discovered and produced, the exploration work is gradually shifting to deeper, more changeling targets. This paper is aiming to provide possible vertical depth limits of potentially commercial reservoirs in a basin, and therefore lower the exploration risks. This study utilizes a large quantity of geochemistry and reservoir property data collected from 6 major, oil- and gas-producing basins in China as well as other major petroliferous basins around the world. The idea is the hydrocarbon generation and expulsion history of source rocks play a crucial role in the distribution of oil and gas reservoirs in a sedimentary basin. A variety of source rocks, including the Cambrian – Ordovician carbonate, Permian to Triassic marine shales, Carboniferous – Permian coals, and Paleogene lacustrine shales are included in the study and these source rocks have remarkably different TOCs and thermal maturities. It's quite clear that this paper

shows an objective of significant importance to the oil industry and lays a robust foundation in terms of dataset. This paper uses the hydrocarbon generation potential index ("S1+S2"/TOC) as the key method to determine the ASDLs. This method was proposed more than 10 years ago and has been successfully applied in a number of petroliferous basins in China (including those 6 basins in this study). From numerous previous studies, the changes of the hydrocarbon generation index with thermal maturity (Ro) or depth can be used to simulate the amount of hydrocarbon generated and expelled from source rocks in the geologic history. In the meantime, the maximum depth or thermal maturity can also be determined when the hydrocarbon potential approaches to zero. The results from this method are very consistent with those ASDLs determined from other geochemical parameters as well as the exploration results. In my opinion, there are two things need be cleared:

(1) First, how to determine the trends of the envelope lines indicating the change of the hydrocarbon potential index with depth or thermal maturity. Numerous studies have been done and published using this method in a number of basins in China. Detailed work has been conducted on source rocks with different kerogen types. The hydrocarbon generation potential indexes of these different types of source rocks all displayed similar trends (kind of like bell-shape) with depth or thermal maturity. But different source rocks showed very different hydrocarbon expulsion thresholds and efficiencies. These varying scenarios have been built on actual geochemical data and subsequently modelled by computer. Therefore, the envelop lines in this study are not randomly drawn but are guided by those well-established models. This has to been clearly explained because it is critical for the determination of the ASDLs.

Response: Thank you for your insightful suggestions. We agree with the reviewer that the model is well-established and supported by numerous successfully applied cases in Chinese basins. As the reviewer suggested, we have clarified the determination of those envelope lines in the revised manuscript and provided more references for the scientific community to review.

Changes: We have added a part of content in section 3.1 clarifying the determination of envelope lines, and the detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

The references added are listed here:

1. Zhou, J., & Pang, X. Q.: A method for calculating the quantity of hydrocarbon generation and expulsion. Petroleum Exploration and Development, 29(1), 24-27, 2002.

2. Pang, X., Li, S., Jin, Z., & Bai, G.: Quantitative assessment of hydrocarbon expulsion of petroleum systems in the Niuzhuang sag, Bohai Bay Basin, East China. Acta Geologica Sinica ‐ English Edition, 78(3), 615-625, doi:10.1111/j.1755-6724.2004.tb00174.x, 2004.

3. Jiang, F., Pang, X., Bai, J., Zhou, X., Li, J., & Guo, Y.: Comprehensive assessment of source rocks in the Bohai Sea area, eastern China. AAPG Bulletin, 100(6), 969-1002, doi.org/10.1306/02101613092, 2016.

4. Peng, J., Pang, X., Shi, H., Peng, H., & Xiao, S.: Hydrocarbon-generation potential of upper Eocene Enping Formation mudstones in the Huilu area, northern Pearl River Mouth Basin, South China Sea. AAPG Bulletin, 102(7), 1323-1342, doi:10.1306/0926171602417005, 2018.

(2) Second, this study proposes a linear equation to predict ASDL using basin heat flow data. It looks pretty good with the data from the 6 basins in the study, but there are only 6 data points. Statistically, the prediction is not be that robust. Two other things may also cause inaccurate predictions using this equation. First, basin heat flow (HF) can vary significantly over the geologic history. This paper did not clearly state the heat flow is the paleo-HF or present HF of the basins. Second, I assume the depth is the present-day burial depth, which can be very different from the maximum burial depth in the basin history, especially foreland basins (e.g. Appalachian Basin, USA). The late-stage uplifting in the Appalachian Basin can be up to thousands of meters. Marcellus Shale in the northeast Pennsylvania, for example, shows very high thermal maturity (3 – 4.5% Ro) and in some area, has passed the ASDL, but the present-day depth generally is less than 3 – 4 km. In contrast, some rifted basins have never undergone any uplifting at all. Given the complex geologic histories of some basins, thermal maturity (Ro) appears to be more reliable (also pointed out in this paper). Although different types of basins are included in the study and the predicted ASDLs appear to be very reasonable, it would be nice to run some blind test including some data from basins in other continents. Also, it would be great to add some assumptions regarding the possible limitations of this application. In summary, this paper has a well-defined objective, a huge amount of data, a well

proved methodology, and very solid results. The publication of this paper will bring a remarkable impact to the oil industry and the new findings from this paper surely will help lower exploration risks.

Response: Thank you for your insightful comments. The heat flow used in this study is the present heat flow value of a basin. As suggested by the reviewer, burial history could have a great impact on ASDL, and we have already discussed it in the manuscript and proposed similar conclusions that the depth corresponding to ASDL should be utilized carefully in the superimposed basin, and that thermal maturity is more suitable to characterize ASDL. On the other hand, the reviewer has also mentioned the blind test of our model in other basins. However, as we mentioned in the reply to the reviewer György Pogácsás, the equation proposed by our previous manuscript is only to demonstrate the existence of relationship among heat flow, organic matter type and the ASDL, instead of predicting the ASDL of a basin by the equation. This is because two other important factors have not been incorporated into the equation of which the establishment is limited by our database. Therefore, the construction of a complete model or equation still needs help from the scientific community to enrich the relevant database.

Changes: We have re-written section 3.3 according to the above response, and the detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

Short Comment #3 by Zhihong Pan

General Comments: Fossil fuel resources play an important role in the modern life. As the increasing demand of hydrocarbon, how to streamline the exploration is of great significance. As is well known, the vertical distribution of hydrocarbon varies from several hundred meters to tens of kilometers, which can bring high risks to the oil and gas assessment and exploration. This paper introduces an innovative concept: Active Source Rock Depth Limits (ASDL), which defines the maximum burial depth for source rocks to generate hydrocarbon in sedimentary basins. The concept can significantly provide guidance for hydrocarbon assessment and exploration. Detailed examples from six major petroliferous basins in China have been presented. The method used to define ASDL is very solid, parameters applied in this paper like H/C ratios, "A"/TOC, "S1+S2"/TOC are widely used in organic geochemistry. The result shows the existence of ASDL, and it is comparable across these basins

regarding thermal maturity. Apart from the basins in China, the paper also shows the concept of ASDL is applicable to the basins all over the world, which strongly support the authors' idea. Moreover, the controlling factors of ASDL has been investigated in the paper and the authors point out the ASDL is mainly constrained by the heat flow of the basin and types of organic matter. Quantitative research in hydrocarbon geology has always been a challenging task, however, through geochemical and mathematical analysis, the quantitative relations between the above two controlling factors and ASDL is established in this paper, which is a good try. At the ending part of the paper, the authors come up with the idea that the petroliferous basin can be vertically divided into three parts based on HET, oil and gas supply limits, and each part has its own types of hydrocarbon reservoirs. The idea provides a more efficient way to target hydrocarbon reservoirs, which is very interesting and hopefully we can see more details about this in the future. Honestly speaking, I believe the work of this paper is very innovative and the result is very solid, and it provides us with a new perspective when doing fossil fuel exploration, which definitely deserves to be published. However, I still have few suggestions and comments for this paper:

(1) Geochemical data and hydrocarbon reservoir parameters from six representative petroliferous basins in China are quite enough. I am not sure whether the corresponding dataset for basins from worldwide is accessible, like Persian Gulf Basin, West Canada Basin, North Sea Basin. If one or few detailed examples of above mentioned basins can be presented, it would be the icing on the cake.

Response: Thanks for your comment. The datasets from global basins are mainly sourced from IHS (2010), which mainly contains datasets related to basins and hydrocarbon reservoirs rather than these geochemical data with source rocks.

Changes: According to the above response to the reviewer, there is no change in the revised manuscript related to this comment.

(2) In the part of quantitative prediction of ASDL, the predicted ASDL can be expressed by HI and HF, where HI is the proxy of organic matter types. As we all know, there are some other parameters can represent kerogen type, why the HI is selected to establish the quantitative relation in this paper?

Response: Thanks for your comment. It is true that many different methods could be taken to identify the organic matter type, and it is also feasible to convert the organic matter type parameters obtained by other methods into HI. However, there are two main reasons for selecting the hydrogen index (HI) as the input of our model. First, HI is a quantitative proxy for the characterization of kerogen types, and it can be easily obtained through Rock-Eval analysis. Numerous studies on source rock evaluation from the scientific community have proven the dependability and reliability of HI. Furthermore, HI has been widely chosen as the indicator of kerogen type in professional software such as PetroMod that is often utilized by the industrial community. Therefore, from the perspective of scientific and industrial community, HI is capable of serving as an input parameter to our model to indicate organic matter types.

Changes: According to the above response, we have added the reason in section 3.3 for using hydrogen index as the proxy of organic matter type, and the detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

(3) In part 3.1, the average thermal maturity level is regarded as the identification criterion for ASDL in general geological settings. However, in part 3.3, the quantitative prediction of ASDL is express by active source rock depth limit. As is known, the thermal evolution of organic matter is a chemical process and it is a function of time and heat. Therefore, I believe if we want express ASDL by depth, it is better to take the age of source rock into consideration when doing quantitative investigation.

Response: Thanks for your comment. We agree with the reviewer that the quantitative model with the stratigraphic age taken into consideration is much more rigorous. However, as we mentioned in the reply to reviewer György Pogácsás, the ASDL is not only influenced by the heat flow and organic matter type, but also influenced by the stratigraphic age and tectonic uplift. To set up the equation with four independent variables, at least twelve equations with different variables should be applied. This is, however, not satisfied by our database since we only have datasets from six basins. It looks promising to construct a complete model or equation if more and more other basins' ASDLs are unravelled.

Changes: We have re-written section 3.3 according to the above response, and the detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

(4) In part 3.3, it seems that the HF used here is the value of nowadays. But HF varies in geological history and can be influenced by tectonic events. For example, the current heat flow in Basin and Range is high due to the recent tectonic extension. Therefore, maybe an average heat flow from the time when the source rock deposited to present is a better.

Response: Thanks for your comment. In our revised section 3.3, the equation only shows that there exists a relationship between heat flow and organic matter type and the ASDL, and the equation cannot be used to precisely predict the ASDL of a basin. We argue that it is better to predict the ASDL with the criteria provided by our study (i.e. Ro=3.5% ± 0.5%) through the basin modelling. We have tested the relationship between average paleo-heat flow and the ASDL, and an obvious negative relationship was observed, the same with the relationship between present average heat flow and the ASDL. Since the evolution processes of different basins are very complicated and the heat flow both in the present and in the geological past contribute to the thermal maturation of source rocks, it is therefore unnecessary to separate them if we only want to prove there is a relationship between heat flow and ASDL.

Changes: We have re-written section 3.3 according to the above response, and the detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

(5) In conclusion 1 and 2, what is meaning of ASRL? Is this a typo or Does it represent something else?

Response: It should be ASDL rather than ASRL. We are sorry for the confusion caused by the typo, and we have modified it in a revised manuscript.

Changes: We have revised the ASRL into the ASDL.

Short Comment #4 by Fengtao Guo

General Comments: I find this manuscript is generally well written, structured, and illustrated. Some of the results are very interesting and thought-provoking. It puts forward the concept of "Active Source Rock Depth Limits (ASDL)", and try to characterize the vertical depth distribution of discovered reservoirs. A

huge of data has been systematically compiled around the world, especially the six key basins in China. The use of four methods to characterize and corroborate the ASDL, including the possibility to be used around the world, makes it more convincing. The controls on the ASDL are also explored and a quantitative model was established to predict the results. The study is very meaningful in the way that it is the first systematic attempt to work on the relationship of depths and hydrocarbon reservoirs, especially on such a huge scale around the world, with so much data. It brings this topic to our attention which should be studied before. The topic has great scientific values. It could help us to better understand why at a shallow depth there are no reservoirs in a basin whereas in some other basins, reservoirs are found in a much deeper layer. If proven, it will also help us to determine whether to drill a well to a certain depth. During my reading of this MS, I had several questions or suggestions for the authors. If they could help with them, I would really appreciate it.

(1) The ASDL was mostly established with the data of six basins in China, although data of basins around the world (IHS, 2010) were later used to verify the ASDL. Is it possible to incorporate some basins outside of China in the process of establishing the model? I totally understand this is totally a data issue and the authors may not be able to get enough systematic data of basin around the world as in China. However, this could be an improvement, if possible.

Response: Thanks for your suggestion. We agree with the reviewer that incorporating more basins into the model is much better for establishing a complete mode. As pointed out by the reviewer, however, we cannot get the geochemical data of source rocks like ours.

Changes: According to the above response to the reviewer, there is no change in the revised manuscript related to this comment.

(2) In section 3.3, the authors used the average values (heat value, depth, HI) of each basin to verify the model of ASDL, it is generally OK and understandable as there must be lots of data for each basin. However, is there still any possibility that some outliers may be present? If yes, how to explain them?

Response: Thanks for your comment. In the section 3.3, the HI value is given according to source-rock general property, while the average heat flow of each basin is sourced from numerous literature, and the average depth of ASDL for each basin is obtained from various indicators as proposed in the manuscript. Therefore, the average heat flow and depth of ASDL for each basin may be the source of some outliers which could be caused by experimental errors. However, we have discarded the outliers during the compilation of these data.

Changes: According to the above response to the reviewer, there is no change in the revised manuscript related to this comment.

(3) In section 3.4, the authors proposed the concept of Hydrocarbon Reservoir Depth Limit (HRDL), mentioning that "at some depth (Hydrocarbon Reservoir Depth Limit), the probability of drilling oil or gas reservoirs decreases to zero", and talks a bit about the relationship between HRDL and ASDL. I think this is an important part as for a hydrocarbon reservoir to form, it requires both hydrocarbons from source rocks and reservoirs rock to accumulate. Unfortunately, very little was discussed on the HRDL in this point. If possible, could more details be added on this?

Response: Thanks for your suggestion. The HRDL is modified as HADL in the revised manuscript, and we have added relevant content in the revised manuscript. The HADL is a newly proposed concept by the first author, which is influenced by many different factors and we will discuss it in the other paper.

Changes: We have modified section 3.4 according to the above response, and the detailed revisions can be found at the end of this response, which is attached as a marked-up manuscript.

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

Active Source Rock Depth Limit and its Controlling on the Formation and Occurrence of Fossil Fuel Resources

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Abstract. Fossil fuel resources are invaluable to economic growth and social development~~wealth given to human beings by nature~~. Understanding the formation and distribution of fossil fuel resources is critical to the search and exploration of them.~~Many mysteries related to them have been revealed such as the origin time and distribution area,~~ Until now, ~~but their~~the vertical distribution depth of fossil fuel resources has not been confirmed due to~~for people's~~ different understandings of their origins and the substantial ~~big depth~~ variation~~s~~ of reservoir depths 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~~ were examined to identify the maximum burial depth of active source rocks in each basin, which is named in this study as the active source rock depth limit (ASDL).~~study their Active Source Rock Depth Limits (ASDL), defined in this study as the maximum burial depth of active source rocks beyond~~ Beyond ASDL, ~~which th~~e source rocks no longer generate or expel hydrocarbons and become inactive~~, to identify the maximum depth for fossil fuel resources distribution~~. Therefore, ASDL also sets~~Theoretically,~~ the maximum depth for~~the ASDLs of~~ fossil fuel resources. The ASDLs of basins over the world are found to range~~s~~ from 3,000 m to 16,000 m, while the~~ir~~ thermal maturities (Ro) of source rocks at the ASDLs are almost the same, with Ro≈3.5±0.5%. The Ro of 3.5% can be regarded as a general criterion to identify ASDLs. ~~A higher~~ High heat flow and more oil-prone kerogen are associated with~~a~~ shallow~~er~~ ASDLs. In addition, tectonic uplift of source rocks can significantly affect ASDLs. ~~Active source rocks and the discovered~~ 21.6 billion tons of reserves in six representative basins in China and 52,926 documented oil and gas reservoirs in ~~the~~ 1,186 basins over the world are all located ~~found to be distributed~~ above ~~the~~ ASDLs, demonstrating the universal presence of ASDLs in petroliferous basins and their control on the vertical distribution of fossil fuel resources.

~~illustrating the universality of such kind of depth limit.~~ The data used in this study are deposited in the repository of the PANGAEA database: https://doi.pangaea.de/10.1594/PANGAEA.900865 (Pang et al., 2019).

Keywords: Fossil fuels; Nature energy; 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~~ the world economy, a lot of research have been done on fossil fuels in the past few decades, ~~many mysteries related to fossil fuel resources have been uncovered,~~ including characterizing and explaining their spatial distribution in various types of sedimentary basins (Tissot & Welte, 1978; Wang et al., 1997; Gautier et al., 2009) and their temporal distribution through the past~~about~~ 1.6 billion years in the geological history (Wang et al., 2016). However, the vertical distribution of fossil fuel resources, especially the maximum preservation depth,~~i.e. the maximum depth, has not been confirmed~~ is still under debate because of ~~people's~~ different understandings of the fossil fuel resource ~~their~~ origins and the great ~~their big depth~~ variations of depths 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 fuel~~s~~ exploration is rapidly expanding to more challenging and deep regions of the 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~~ are mainly found in the Tarim ~~basin~~ Basin, where the amount of deep oil and gas reserve is estimated to account for more than 90% of the total proved reserves ~~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~~initiated research programs developing 10,000 ~~-~~m ~~-~~scientific drilling rigs, and funded the National Basic Research Program (973 Program) to better understand hydrocarbon accumulations deep in basins~~probe deep hydrocarbon accumulations~~ (Jia et al., 2016). One ~~big~~ major challenge for deep oil and gas exploration comes from the significant variation of ~~great variety of~~ reservoir depths in different basins and the uncertainty it poses to oil and gas resource~~s~~ assessment. In some basins, dry layers, ~~objective~~ target 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~~more than 10,000 m. To date, the maximum depth to which fossil fuels can be formed and preserved in the Earth's crust remains unresolved~~is still a mystery~~. Some ~~R~~researchers support~~ing~~ the abiogenic petroleum origin and believe that the maximum depth of hydrocarbon occurrence is much deeper than the maximum depth of petroliferous basins ~~itself~~ (Gold, 1993; Kenney et al., 2002)~~;~~. However, more and more researchers believe that oil and gas are of biogenic origin and suggest that the maximum depth of oil and gas reservoirs is critically controlled by the depth of active source rocks which generate and expel oil and gas in sedimentary basins~~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 in China, which have the largest areas, the largest proved oil and gas reserves and the highest exploration degrees ~~in China~~ (Fig. 1, Table 1), to identify the maximum depth of fossil fuel resources in each basin and investigate factors leading to the variation of the maximum depth from one basin to another. ~~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 are proved and widely accepted~~has been proved~~ (Magoon & Dow, 1994; Peters et al., 2005). Besides,~~ and~~ no commercial petroleum reservoirs of abiogenic origins have been discovered to date~~so far~~ (Kenney et al., 2002; Glasby, 2006; Höök et al., 2010; Selley & Sonnenberg, 2014). In this study, ~~G~~geological and geochemical data of 13,634 source rock samples from 1,286 exploration wells in six~~these~~ basins were ~~have been~~ examined~~, and~~. ~~t~~The maximum depth for the formation and occurrence of fossil fuel resources in these basins were determined~~have been identified,~~. Major geological factors ~~as well as the major factors~~ influencing the maximum depths of active source rocks were analysed and their controlling on the distribution of fossil fuel resources were ~~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~~ mapped according to Zhu (2011).

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 the Bohai Bay Basin in ~~the e~~Eastern China, the Sichuan Basin and the Ordos Basin in ~~the c~~Central China, and the Tarim Basin and the Junggar Basin in ~~the w~~Western China. ~~Within~~ For each basin, we utilized at least four different indicators detailed in the Section 2.2 ~~reported in the next section (Characterization of ASDLs)~~ to determine the ASDL~~s~~. The data were obtained ~~necessary for identifying the ASDLs was obtained~~ from PetroChina and Sinopec~~, respectively. The dataset can be accessed~~ and are available through the PANGAEA database: https://doi.pangaea.de/10.1594/PANGAEA.900865 (Pang et al., 2019). We ~~further~~also investigated the relationships of ASDLs and the distributions of 52,926 reservoirs in 1,186 basins over the world according to the database of IHS (2010) to verify its universality.~~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 A~~Active source rocks are sedimentary rocks rich in organic matter and capable of generating hydrocarbons. In the evolution history of a basin that spans over millions of years~~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~~ With further increase~~ing~~ of burial depth of the source rocks, the potential amount~~s~~ of hydrocarbons that can be produced and expelled from the source rocks decreases and eventually ~~goes~~ approaches ~~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 physical parameters of source rocks~~critical conditions~~, such as the thermal maturity. ~~(Ro) of the source rocks.~~

The potential amount~~s~~ 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 number ratios of hydrogen to carbon (H/C) and oxygen to carbon (O/C) of the remaining organic matter in the sample~~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 studied ~~investigated~~ by measuring the decrease in the H/C and O/C ratios (Tissot et al., 1974). In theory, ~~kerogen~~organic matter in source rocks eventually evolves ~~in~~to graphite with increasing thermal maturity with the H/C and O/C ratios drop to zero~~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~~identify the ASDL such as the hydrocarbon generation potential index (“$S_1 + S_2$”/TOC). “S_1” is the amount~~s~~ 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 sample (Espitalie et al., 1985). The concept of the hydrocarbon generation potential index was proposed by Zhou and Pang (2002). Pang et al. (2005) used the index to measure the quantity of hydrocarbons that can be generated from a single unit weight of organic carbon. The ~~hydrocarbon generation potential~~ index ~~of the source rocks first~~ generally increases with increasing burial depth when the thermal maturity is low and then decreases with increasingly higher burial depth or thermal maturity. ~~and then decreases with increasing burial depth~~. The turning point of hydrocarbon generation potential index corresponds to the hydrocarbon expulsion threshold (HET) which was proposed by Pang et al. (1997). ~~It~~HET represents that hydrocarbons start migrating out of source rocks to surrounding reservoirs ~~the source rocks begin expelling hydrocarbons~~. As the expulsion continues, ~~hydrocarbon expulsion of the source rock increases,~~ the hydrocarbon generation potential index ~~of the source rock~~ gradually decreases.~~depletes, and w~~ When the ~~hydrocarbon generation potential~~ index approaches zero, ~~the~~ source rocks can no longer expel hydrocarbons and reach~~es~~ the ASDL. ~~During~~ Along with the evolution of hydrocarbon generation potential index, the hydrocarbon expulsion ratio (Qe), hydrocarbon expulsion rate (Ve) and hydrocarbon expulsion efficiency (Ke) of the source rocks also ~~change~~ evolve with thermal maturity~~regularity~~. ~~Hydrocarbon expulsion ratio~~Qe represents the amounts of hydrocarbons expelled from a~~ single~~ unit weight of organic carbon. ~~Hydrocarbon expulsion rate~~Ve represents the hydrocarbons expelled from a~~ single~~ unit weight of organic carbon when the burial depth increases by 100 m.~~, and the hydrocarbon expulsion efficiency~~ Ke represents the ratio of the cumulative amount~~s~~ of hydrocarbons expelled from source rocks to the 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, h~~Hydrocarbon generation is the transformation of original organic matter ~~(kerogen)~~ , also referred to as kerogen, to transitional compounds and finally to hydrocarbons (Behar, et al., 2006). ~~Therefore, w~~When the amount of transitional compounds or~~ the~~ residual hydrocarbons (“S_1” or “A”) decrease to zero, ~~tend to disappear indicating that~~ the hydrocarbon generation potential is also exhausted. Experimentally, “A” is the amount~~s~~ of hydrocarbons extracted by a chloroform solution from a source rock sample. Because some non-hydrocarbon compounds are~~matter can~~ also ~~be~~ extracted, “A” is~~values are~~ generally larger than “S_1” ~~values~~. The residual hydrocarbon content index (“S_1”/TOC or “A”/TOC), which represents the ~~representation of~~ quantity of hydrocarbons retained per ~~that are retarded in a single~~ unit weight of organic carbon, can therefore be used to ~~measure~~ indicate the ASDL. Previous stud~~y~~ies (Zhou and Pang, 2002; Pang et al., 2005) indicate~~s~~ that ~~the~~ source rocks reach HET ~~entered hydrocarbon expulsion threshold~~ when the residual hydrocarbon content index ~~reached~~ reaches ~~the~~ its maximum value. After that, ~~and since then, such~~ the index began to decrease. The source rocks finally evolve to pass the ASDL to become inactive when ~~enter the state of ASDL when~~ the residual hydrocarbon content index decreases to a minimum value. In summary, the parameters listed in the section, including H/C, O/C, “$S_1 + S_2$”/TOC, “S_1”/TOC, “A”/TOC, Ve and Ke, all trend as a function of source rock burial depth (D) or thermal maturity (Ro).~~This study analysed trends of these parameters as a function of depth (D) or thermal maturity illustrated by measured vitrinite reflectance (Ro).~~ The ASDL can thus be ~~is thus~~ represented as the critical values of ~~level of~~ D or Ro when~~where~~ the indexes of H/C, O/C, “$S_1 + S_2$”/TOC, “S_1”/TOC, “A”/TOC, and Ve approach zero, or when~~and~~ Ke approaches a constant value.

3 Results and Discussions

3.1 ASDLs in the Six Representative Basins

~~In this study, we characterized t~~The ASDLs of~~in~~ the six representative basins were characterized~~of China~~. The ~~main text takes the~~ Junggar Basin located in ~~western~~ Western China is used 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~~the other five basins, and the results are shown in Figs. S1–S5 and Table 2. The hydrocarbon formation and accumulation in the Junggar Basin are mainly controlled by the Permian petroleum system (Wang et al., 2001). Previous geochemical and sedimentological data demonstrate that the source rocks are mainly Permian shales and that the main reservoirs are the clastic rocks in the Permian, the Triassic, and the Jurassic Formations capped by the Upper Triassic, the Lower Jurassic, and the Lower Cretaceous mudstones, respectively (Cao et al., 2005). A few Carboniferous volcanic reservoirs are found distributed in structural highs near fault zones and unconformities, the hydrocarbons in these reservoirs are also primarily derived from the Permian shales

(Chen et al., 2016; Wang et al., 2018). According to the analyses of fluid inclusions and basin modelling, the Permian source rocks started generating hydrocarbons since the Middle-Late Permian due to a rifting process-related high heat flow, and the main hydrocarbon accumulation period spanned from the Triassic to the Paleogene for the whole basin (Wang et al., 2001; Cao et al., 2005). Petroleum systems in the other five basins were studied by other researchers (Zhou and Littke, 1999; Xiao et al., 2005; Wu et al., 2008; Ping et al., 2017; Zhu et al., 2018).

In the Method Section, we provided theoretical threshold values of different geochemical parameters or indexes to indicate ASDL. In practice, envelope lines enclosing all sample data points are utilized to show the overall trends of how these parameters change with increasing burial depth or thermal maturity. The interceptions of the envelope lines with these threshold values represent source rocks reaching ASDLs. This envelop method has been widely and successfully employed in a variety of basins in China, and numerous studies containing different geochemical data and mathematical models have been published (Zhou and Pang, 2002; Pang et al., 2004; Jiang et al., 2016; Peng et al., 2018). It is found the profiles of hydrocarbon generation potential index, Ve, and residual hydrocarbons are overall bell-shaped, though details can vary depending on the source rock types (e.g. different lithologies and organic matter types). On the other hand, some uncertainties may exist in the envelope method due to the lack of data from ultra-deep wells. In this case, the ASDLs can be identified by extrapolating the profiles according to the variation trends established based on the available data at different burial depths or thermal maturities. The envelope lines employed in this study are guided by well-established models and trends derived from actual geochemical data.

Figure. 2a shows H/C ratios ~~versus depth~~ of source rock samples from the Permian shales plotted against burial depth~~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 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. The mean reached the~~A~~ maximum ~~is reached~~ at ~~a~~the 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~~ eventually reaches zero at a depth~~the ASDL~~ of 7,850–7,960 m and a~~with~~ corresponding Ro of 3.0%, indicating the ASDL. 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~~indicate an ASDL of 8,200 m with ~~corresponding~~ Ro of 3.0%, in good agreement with the ASDL values obtained in Fig. 2a and 2b. ~~Besides~~In addition, the HET is determined to be D of 3,000 m and Ro of 0.9%, and the hydrocarbon expulsion peak occurs at D of 4,500 m and Ro of 1.3%.

Figure 2: ~~The i~~Identification of ASDL in the Junggar Basin using different indicators,~~.~~ including ~~a,~~ the variation of H/C ratios (a), residual hydrocarbon amounts (b), “$S_1 + S_2$”/TOC (c1), Qe (c2), Ve (c3) and Ke (c4) with depth.~~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 identified for ~~in~~ the six representative basins (Table 2), three general conclusions on ASDL can be drawn~~kinds of features of ASDLs can be drawn from them~~. First, for the same basin, the ASDLs ~~of the same basin~~ derived from the six geochemical indexes are the same or very close in values. For the Junggar Basin,~~example,~~ the derived ~~depths of the~~ ASDLs ~~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 r~~epresentative~~ basins range between 5,280 m and 9,300 m with an average value of 7,094 m and a deviation of >76.1%. Third, for all the ASDLs of the six ~~representative~~ basins, the corresponding thermal maturities (Ro) 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% derived in this study 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 o~~Original organic matter (or kerogen) in source rocks~~, named as kerogen,~~ is generally classified into three types based on its origin (Peters, 1994; Tissot et al., 1974). The three types have ~~It has~~ different organic element compositions and different pyrolytic parameters, and therefore have~~has~~ different hydrocarbon generation potentials. The hydrocarbon generation potential indexes of different type source rock samples from the representative basins are plotted in Fig. 3. ~~Similarly, t~~The dashed curves enveloping all the sample data points ~~values~~ indicate~~s~~ 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 for all three organic matter types: the index first increases with increasing Ro and ~~first and~~ then decreases after source rocks reach HET~~with increasing Ro~~. ~~The intercept of the dashed lines on the vertical axis marks the ASDLs for different organic matter types.~~ Source rocks with type I (oil-prone), type II, and type III (gas-prone) kerogens reach ASDLs at Ro of 3.0%, 3.5% and 4.0%, respectively.~~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 than the other two types of source rocks under similar geological conditions.

Figure 3: ~~Investigation of the influence~~Effects of kerogen types on ASDLs represented by thermal maturity (Ro). From left to right are three plots of hydrocarbon generation potential index versus Ro for source rocks of Type I (a), Type II (b), and Type III (c).~~, 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

ASDLs are~~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~~ Western China ~~are characterized with~~have 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~~ 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~~ Central China are moderate in terms of heat flow and geothermal gradient, and the depths of ASDLs ~~change~~ vary from 6,600 m to 7,700 m. In addition, the source rock burial depths corresponding to HETs vary similarly: high heat flow and high geothermal gradient lead to shallow HETs ~~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).

Figure 4: Variation of ASDLs in the six representative basins due to different heat flows . The ASDLs of different petroliferous basins are characterized by hydrocarbon generation potential index (represented by "$S_1 + S_2$"/TOC). 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.

3.2.3 Tectonic movement, stratigraphic age and other factors

~~In fact, the~~ ASDL is also influenced by other two important factors,~~some other factors,~~ i.e. ~~such as~~ tectonic uplift and ~~the~~ stratigraphic age of source rocks. As previous stated, ~~the~~ ASDL is better~~mainly~~ characterized by thermal maturity than by depth, 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 were~~was~~ historically uplifted after reaching the original ASDL~~s (Ro=3.5%)~~ is relatively shallower compared with ~~those~~ younger source rocks that were not uplifted. The Sichuan ~~basin~~ 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 rocks is about 1.0% at the depth of ~2000 m in the ~~southern~~ Southern Sichuan basin (Zhu et al., 2016). At the same burial depth ~~of southern Sichuan basin~~, however, the Ro of the lower Triassic source rocks can reach ~~about~~ 2.0% (Zhu et al., 2016). Therefore, ~~the~~ tectonic uplift and ~~the~~ stratigraphic age of source rocks can have a significant effect ~~an influence~~ on the corresponding depth of ASDL.

In addition to the mentioned four main factors, deep thermal fluids and overpressure retardation may also affect ASDL (McTavish, 1998; Hao et al., 2007; Fetter et al., 2019). Although it is not the scope of our study to investigate every single influence factor of ASDL in detail, we present a brief introduction to the possible consequence of these factors. Deep thermal fluids provide both fluids and a thermal source, and can facilitate the maturation of organic matter. On the one hand, the conduction of thermal fluids through rocks and faults brings thermal energy to source rocks and promotes source rock maturation and hydrocarbon generation (Rullkötter et al., 1988). On the other hand, the H_2 brought by the deep fluids can considerably improve the hydrocarbon generation rate through the kerogen hydrogenation process (Zhu et al., 2017). Consequently, compared with unaffected source rocks, source rocks influenced by deep thermal fluids may have shallower ASDLs. In terms of overpressure retardation, an overpressure on source rocks can retard the thermal evolution of hydrogen-rich kerogen and/or the thermal cracking of hydrocarbons (McTavish, 1998; Hao et al., 2007). As a result, source rocks influenced by overpressure retardation have deeper ASDLs. It is worth noting that the thermal maturity corresponding to ASDL remains the same, no matter the ASDL becomes deeper or shallower. Namely, a source rock will reach ASDL when its Ro increases to 3.5% ± 0.5% and its hydrocarbon generation potential is depleted. Therefore, we argue that the thermal maturity of organic matter is more suitable to characterize ASDL than depth.

~~**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 relationship between ASDL and heat flow and organic matter type~~Quantitative prediction of ASDLs~~

According to the analysis in the previous section, heat flow and organic matter type act as the two main factors controlling ASDLs. In this section, a quantitative relationship is further established by statistics using the software Origin 2019. We first analysed the depths of ASDLs as a function of heat flow with a linear model. The ASDL for each basin is the average depth obtained from various geochemical indicators. The heat flow utilized in the model is the average of present heat flow values measured at different locations in each basin (Table 1). A strong negative correlation is observed between the ASDLs and the present heat flows with a coefficient larger than 0.9 (Fig. 5a), indicating that high heat flow very likely leads to a shallow

ASDL. Considering that the heat flow values of a sedimentary basin vary with geologic time, the average heat flow since the deposition of source rocks was further employed. As shown in Fig.5a, the ASDLs also present an obvious negative correlation with average paleo-heat flows. This implies that the paleo and present heat flows both contribute to the thermal maturation of source rocks and therefore play an important role in controlling the ASDLs. We mainly utilize the present heat flow values in the following discussion, mainly because the correlation (R=0.90) between ASDL and present heat flow is much higher than that (R=0.77) between ASDL and the average value of paleo-heat flow. It is also observed that the maximum buried depth of oil-bearing targets in most basins is mainly corresponding to the maximum temperature under the current heat flow. ASDLs for basins of different current heat flows range between 3,000 m and 16,000 m. Generally, ASDLs are less than 6,000 m in basins with high heat flow (>70 mW/m^2), and are greater than 9,000 m in basins with low heat flow (<40 mW/m^2). Given that ASDL is also influenced by organic matter type, we further analysed the effects of organic matter type on ASDL by adding the hydrogen index (HI), an indicator of organic matter type, to the linear model. HI is a quantitative proxy for the characterization of kerogen types, and is easily obtained through Rock-Eval analysis. Numerous studies on source rock evaluation from the scientific community have proven the reliability of HI. Furthermore, HI has been widely chosen as the indicator of kerogen type in professional software, such as PetroMod, which is often used by the industrial community. To quantify the influence of organic matter types on ASDLs, the 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 are assigned to type I, I–II, II, II–III and III kerogens, respectively. The following equation is then deduced:

$$\mathrm{ASDL} = 16448 - 3.61 * \mathrm{HI} - 139.46 * \mathrm{HF} \qquad (1)$$

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

Although Eq. (1) shows a high correlation coefficient of 0.96 (Fig. 5b), this equation, instead of being utilized to precisely predict the ASDL of a basin, is only presented to confirm the existence of a relationship among the ASDL, heat flow and organic matter type because of the following reasons. First, the variation of organic matter types in our study is relatively small (Table 1), and therefore, the hydrogen index values utilized to deduce Eq. (1) show small variations, which can bring uncertainties to some extent. Second, as mentioned in the above section, the ASDL is not only influenced by the heat flow and organic matter type, but also influenced by the stratigraphic age and tectonic uplift. The Eq. (1), having not included all the 4 major factors, is therefore not sufficient to predict the precise ASDL of a basin. To set up a model with four independent variables, however, is difficult and impossible by our database of 6 basins. Construction of a complete and precise model or equation needs help from the scientific community to enrich the database. We suggest that basin modelling and other integrated analysis methods should be applied if readers want to predict the depth of ASDL in a basin without enough geological and geochemical data. Quantitative relationship indicated in Eq. (1) provides preliminary insights into the geological basis and boundary condition for the prediction of fossil fuel distribution in the basins and helps the evaluation of hydrocarbon potential.

~~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.~~

~~$ASDL = 16202 - 2.63 * HI - 139.46 * HF$, (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 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 the six~~petroliferous~~ basins. a, relationship between ASDLs and heat flows~~and the maximum depths of ASDLs~~. b, the comparison of the modelled depths through Eq. (1) and measured depths of the ASDLs. Basin order: 1. Tarim Basin; 2. Junggar Basin; 3. Sichuan Basin; 4. Ordos Basin; 5. Bohai Bay Basin; 6. Songliao Basin.~~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 in many different industries~~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 all economical ~~favourable~~ hydrocarbon reservoirs. Once the burial depth of organic matter exceeds the ASDL, the hydrocarbons are ~~oil and gas could~~ no longer generated ~~be produced~~ from the source rocks, and the coal ~~which has been evolved~~evolves to graphite ~~would also lose~~losing 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, approximately 97.7% of coal resources in China and 97.3% of recoverable coal reserves over the world are distributed above ~~the~~ ASDLs corresponding to Ro of 4.0% (CCRR, 1996; CNACG, 2016; Conti et al., 2016). Therefore, ASDL ~~controls~~ represents 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 in the ~~W~~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 the 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 trends ~~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). The data show that all the reservoirs in the six basins distributed above the ASDLs~~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 commercial 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, and this depth is regarded as the Hydrocarbon ~~Reservoir~~ Accumulation Depth Limit (~~HRDL~~HADL). Similar to ASDL, HADL is also influenced by many factors such as the hydrocarbon phases, the geothermal field, the strata age and lithology of the reservoir, and will be discussed in other papers. Here, we just focus on the relationship between HADL and ASDL. The ~~HRDLs~~ HADLs 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. Meanwhile, according to the vertical distribution characteristics of proved hydrocarbon reserves, it is observed ~~discovered~~ that all proved hydrocarbon reserves in the six representative basins are controlled by the ~~HRDL~~ HADLs which is above the ASDLs (Fig. 7; Fig. S6). This means that the HADL in a basin ~~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 in fields with active source rocks ~~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~~ HADL 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~~ are shown in Fig. 8. ASDL for each basin ~~was~~ is assumed to be at Ro of 3.5%, and the corresponding depth is obtained ~~can be calculated~~ from the documented heat flow of that basin. We found that ~~HRDL~~ the HADLs (represented as depth) ~~is~~ are universally above the ASDLs 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~~HADLs. The results include 116,489 samples of target layers from 4,978 exploration wells in China. The blue dashed line represents the evolution of porosity with depth. Its intercept with the line of 2% porosity marks the HADL. ~~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~~ clear that the ~~HRDLs~~ HADLs are always above the ASDLs.

Figure 8: The vertical distribution ~~characteristics~~ of numbers of discovered hydrocarbon reservoirs and their relationships with ASDLs and ~~HRDLs~~ HADLs in the worldwide 1,186 petroliferous basins. a, summation of proven reservoirs in the 1,186 ~~petroliferous~~ basins. b, low~~er~~ heat flow basins (<25 mW/m^2). c, relative low~~er~~ heat flow basins (25–40 mW/ m^2). d, relative high heat flow basins (40–55 mW/ m^2). e, high heat flow basins (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~~HADL. 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.

Hydrocarbons ~~is~~ are 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~~.~~, but ~~T~~this concept can be modified to incorporate the two types of hydrocarbons. Therefore, two ASDLs are introduced, including ASDLg for gas and ASDLo for oil~~, such as ASDL for gas and ASDL for oil~~. ASDLo ~~for oil~~ indicates ~~that the~~ source rocks can no longer generate oil, and is named oil supplying depth limit.~~, while~~ ASDLg ~~for gas~~ indicates ~~that the~~ source rocks can no longer generate gas, and is named gas supplying depth limit. Hydrocarbons generated and exposed from source rocks of low thermal maturities ~~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 ASDLo ~~for oil~~ should be lower than that of ASDLg~~ 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~~ maturity kerogens sampled from Junggar Basin in a closed system. According to the experiment results, source rocks reach~~ed~~ ASDLo~~oil supply limit~~ at Ro of about 2.0% (Fig. 9), and the same source rocks reach~~ed~~ ASDLg~~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 by~~using the~~ ~~high-~~high-temperature and ~~high-~~high-pressure pyrolysis simulation~~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 ASDLo~~oil supply limit (ASDL for oil)~~. b, the variation of gas production rate with Ro and identification of ASDLg~~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 (HET), which marks the starting point of source rocks expelling hydrocarbons at a certain depth. The HET, ASDLo and ASDLg ~~oil supply limit and gas supply limit~~ divide a basin into three regions in the vertical direction~~ along the vertical direction~~, and they control the types of hydrocarbon reservoirs and their distributions (Fig. 10). The upper field ~~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~~ field do not yet expel hydrocarbons. The middle ~~area~~ field (pink area in Fig. 10) is favourable for source rocks to generate, expel and retain hydrocarbons to form various kinds of oil/gas reservoirs, and the source rocks in this field~~area also~~ supply~~ supplies~~ hydrocarbons that may migrate into the upper~~top~~ area. The ~~bottom~~ lower 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 the distribution of HETs and ASDLs. The characteristics ~~for~~of hydrocarbon generation and reservoir~~s~~ distribution differ ~~in~~ among these basins due to their different 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~~upper blue area is favourable for the formation and distribution of conventional oil and gas resources, and hydrocarbons come from the underlying source rocks~~ 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, mainly form conventional oil/gas reservoirs.~~;~~ The ~~bottom~~ lower yellow area is favourable for ~~nature~~ natural gas generation, migration, and accumulation from source rocks, mainly form tight unconventional gas reservoirs~~in this area~~.

4. Conclusions

(1) ASDL is the maximum burial depth for source rocks to generate and expel hydrocarbons from geothermal cracking of kerogen. ASDL marks the depletion of hydrocarbon generation potentials of source rocks, and it commonly exists in petroliferous basins. We found the thermal maturity of 3.5% can be regarded as the identification criterion of ASDL in general geological conditions.~~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 ASDLs of all basins over the world vary from 3,000 m to 16,000 m, and this variation is mainly caused by heat flows, kerogen type, age of source rock strata, and tectonic movement. The ASDL of a basin is deep when the basin's heat flow is low or the source rock kerogen is oil-prone. Tectonic uplift of source rock strata can significantly reduce the ASDL.~~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.~~

(3) All types of fossil fuel resources, including coal, conventional and unconventional oil and gas are formed and distributed above the ASDLs. A basin can be vertically divided into three fields by the HET, the oil supply limit and the gas supply limit. The three fields are favourable for different types of reservoirs.

~~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.

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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References

~~Ajdukiewicz, J. M., & Lander, R. H.: Sandstone reservoir quality prediction: The state of the art. AAPG bulletin 94, 1083-1091, doi:10.1306/intro060110, 2010.~~

Behar, F., de Barros Penteado, H. L., Lorant, F., & Budzinski, H.: Study of biodegradation processes along the Carnaubais trend, Potiguar Basin (Brazil)–Part 1. Organic Geochemistry, 37(9), 1042-1051, doi:10.1016/j.orggeochem.2006.05.009, 2006.

~~Bloch, S., Lander, R. H., & Bonnell, L.: Anomalously high porosity and permeability in deeply buried sandstone reservoirs: Origin and predictability. AAPG bulletin 86, 301-328, doi:10.1306/61EEDABC-173E-11D7-8645000102C1865D, 2002.~~

Cao, J., Zhang, Y., Hu, W., Yao, S., Wang, X., Zhang, Y., & Tang, Y.: The Permian hybrid petroleum system in the northwest margin of the Junggar Basin, northwest China. Marine and Petroleum Geology, 22(3), 331-349, doi:10.1016/j.marpetgeo.2005.01.005, 2005.

CCRR (Editorial committee of China coal resources report) Comparison of coal resources between China and major coal-producing countries. China Coal 7, 68-71, 1996.

Chen, Z., Zha, M., Liu, K., Zhang, Y., Yang, D., Tang, Y., Tang, Y., Wu, K., & Chen, Y.: Origin and accumulation mechanisms of petroleum in the Carboniferous volcanic rocks of the Kebai Fault zone, Western Junggar Basin, China. Journal of Asian Earth Sciences, 127, 170-196, doi:10.1016/j.jseaes.2016.06.002, 2016.

CNACG (China National Administration of Coal Geology) China occurrence regularity of coal resources and resource evaluation. 2016.

Conti, J., Holtberg, P., Diefenderfer, J., LaRose, A., Turnure, J. T., & Westfall, L.: International energy outlook 2016 with projections to 2040 (No. DOE/EIA-0484 (2016)). USDOE Energy Information Administration (EIA), Washington, DC (United States). Office of Energy Analysis. Doi: 10.2172/1296780, 2016.

Dai, J., Yunyan, N. I., Huang, S., Peng, W., Han, W., & Gong, D., et al.: Genetic types of gas hydrates in china. Petroleum Exploration & Development, 44(6), 887-898, doi:10.1016/S1876-3804(17)30101-5,2017.

Durand, B.: Kerogen: Insoluble organic matter from sedimentary rocks. (Editions technip). 1980.

Dyman, T. S., Crovelli, R. A., Bartberger, C. E., & Takahashi, K. I.: Worldwide estimates of deep natural gas resources based on the US Geological Survey World Petroleum Assessment 2000. Natural Resources Research 11, 207-218, doi:10.1023/A:1019860722244, 2002.

Espitalie, J., Deroo, G., & Marquis, F.: La pyrolyse Rock-Eval etses applications. Deuxièmepartie. Revue de l'Institutfrançais du Pétrole 40, 755-784, doi:10.2516/ogst:1985045, 1985.

Fetter, N., Blichert-Toft, J., Ludden, J., Lepland, A., Borque, J. S., Greenhalgh, E., Garcia, B., Edwards, D., Télouk, P., & Albarède, F.: Lead isotopes as tracers of crude oil migration within deep crustal fluid systems. Earth and Planetary Science Letters, 525, 115747, doi:10.1016/0146-6380(88)90237-9, 2019.

Gautier, D. L., Bird, K. J., Charpentier, R. R., Grantz, A., Houseknecht, D. W., Klett, T. R., More, T. E., Pitman, J. K., Schenk, C. J., Schuenemeyer, J. H., Sørensen, K., Tennyson, M. E., Valin, Z. C., &Wandrey, C. J.: Assessment of undiscovered oil and gas in the Arctic. Science 324, 1175-1179, doi:10.1126/science.1169467, 2009.

Glasby, G. P.: Abiogenic origin of hydrocarbons: An historical overview. Resource Geology 56, 83-96, doi:10.1111/j.1751-3928.2006.tb00271.x, 2006.

Global, B. P.: BP statistical review of world energy June 2017. Relatório. Disponível em: http://www. bp. com/en/global/corporate/energy-economics/statistical-review-of-world-energy. html. 2017.

Gold, T.: The Origin of Methane (and Oil) in the Crust of the Earth. USGS Professional Paper, 1570. 1993.

Hao, F., Zou, H., Gong, Z., Yang, S., & Zeng, Z.: Hierarchies of overpressure retardation of organic matter maturation: Case studies from petroleum basins in China. AAPG bulletin, 91(10), 1467-1498, doi:10.1306/05210705161, 2007.

Hayes, J. B.: Porosity evolution of sandstones related to vitrinite reflectance. Organic Geochemistry, 17(2), 117-129, doi:10.1016/0146-6380(91)90070-Z, 1991.

Höök, M., Bardi, U., Feng, L., & Pang, X.: Development of oil formation theories and their importance for peak oil. Marine and Petroleum Geology 27, 1995-2004, doi:10.1016/j.marpetgeo.2010.06.005, 2010.

Hunt, J. M.: Petroleum geochemistry and geology (Vol. 2, pp. 1-743). New York: WH Freeman, 1996.

IHS Energy Group.: International petroleum exploration and production database (Englewood, Colorado: IHS Energy Group). 2010.

Jia, C. Z., Pang, X. Q., Jiang F.J.: Research status and development directions of hydrocarbon resources in China. Petroleum Science Bulletin 01, 2-23, doi:10.3969/j.issn.2096-1693.2016.01.001, 2016.

Jiang, F., Pang, X., Bai, J., Zhou, X., Li, J., & Guo, Y.: Comprehensive assessment of source rocks in the Bohai Sea area, eastern China. AAPG Bulletin, 100(6), 969-1002, doi.org/10.1306/02101613092, 2016.

~~Kennedy, M. J., Pevear, D. R., & Hill, R. J.: Mineral surface control of organic carbon in black shale. Science 295(5555), 657-660, doi:10.1126/science.1066611, 2002.~~

Kenney, J. F., Kutcherov, V. A., Bendeliani, N. A., & Alekseev, V. A.: The evolution of multicomponent systems at high pressures: VI. The thermodynamic stability of the hydrogen–carbon system: The genesis of hydrocarbons and the origin of petroleum. Proceedings of the National Academy of Sciences 99, 10976-10981, doi:10.1073/pnas.172376899, 2002.

Magoon, L. B., & Dow, W. G.: The petroleum system: chapter 1: Part I. Introduction. 1994.

McTavish, R. A.: The role of overpressure in the retardation of organic matter maturation. Journal of Petroleum Geology, 21(2), 153-186, doi:10.1111/j.1747-5457.1998.tb00652.x, 1998.

Pang, X. Q., Jia, C. Z., Zhang, K., Li, M. W., Wang, Y. W., Peng, J. W., Li, B. Y., Chen, J. Q.: Geological and geochemical data of 13634 source rock samples from 1286 exploration wells and 116489 porosity data from target layers in the six petroliferous basins of China. PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.900865, 2019.

Pang, X. Q., Jia, C. Z., & Wang, W. Y.: Petroleum geology features and research developments of hydrocarbon accumulation in deep petroliferous basins. Petroleum Science 12(1), 1-53, doi:10.1007/s12182-015-0014-0, 2015.

Pang, X., Li, M., Li, S., & Jin, Z.: Geochemistry of petroleum systems in the Niuzhuang South Slope of Bohai Bay Basin: Part 3. Estimating hydrocarbon expulsion from the Shahejie formation. Organic Geochemistry 36, 497-510, doi:10.1016/j.orggeochem.2004.12.001, 2005.

Pang, X., Chen, Z., Chen, F. ~~1997.~~ Basic concept of hydrocarbon expulsion threshold and its research significance and application. Geoscience 11, 510-521, 1997.

Pang, X., Li, S., Jin, Z., & Bai, G.: Quantitative assessment of hydrocarbon expulsion of petroleum systems in the Niuzhuang sag, Bohai Bay Basin, East China. Acta Geologica Sinica-English Edition, 78(3), 615-625, doi:10.1111/j.1755-6724.2004.tb00174.x, 2004.

Peng, J., Pang, X., Shi, H., Peng, H., & Xiao, S.: Hydrocarbon-generation potential of upper Eocene Enping Formation mudstones in the Huilu area, northern Pearl River Mouth Basin, South China Sea. AAPG Bulletin, 102(7), 1323-1342, doi:10.1306/0926171602417005, 2018.

Peters, K. E., & Cassa, M. R.: Applied source rock geochemistry: chapter 5: Part II. Essential elements. 1994.

Peters, K. E., Hackley, P. C., Thomas, J. J., & Pomerantz, A. E.: Suppression of vitrinite reflectance by bitumen generated from liptinite during hydrous pyrolysis of artificial source rock. Organic Geochemistry, 125, 220-228, doi:10.1016/j.orggeochem.2018.09.010, 2018.

Peters, K. E., Peters, K. E., Walters, C. C., & Moldowan, J. M.: The biomarker guide (Vol. 1). Cambridge University Press. 2005.

Ping, H., Chen, H., & Jia, G.: Petroleum accumulation in the deeply buried reservoirs in the northern Dongying Depression, Bohai Bay Basin, China: New insights from fluid inclusions, natural gas geochemistry, and 1-D basin modeling. Marine and Petroleum Geology, 80, 70-93, doi:10.1016/j.marpetgeo.2016.11.023, 2017.

Rullkötter, J., Leythaeuser, D., Horsfield, B., Littke, R., Mann, U., Müller, P. J., Schaefer, R.G., Schenk, H.-J., Schwochau, K., & Witte, E. G.: Organic matter maturation under the influence of a deep intrusive heat source: a natural experiment for quantitation of hydrocarbon generation and expulsion from a petroleum source rock (Toarcian shale, northern Germany). Organic Geochemistry, 13(4-6), 847-856, doi:10.1016/0146-6380(88)90237-9, 1988.

Selley, R. C., & Sonnenberg, S. A. Elements of petroleum geology. (Academic Press). 2014.

~~SRCOGR (Strategic Research Center of Oil and Gas Resources, Ministry of Land and Resources) A new round hydrocarbon resource assessment for whole China, Beijing: China Land Press, 2009.~~

Tissot, B., Durand, B., Espitalie, J., &Combaz, A.: Influence of nature and diagenesis of organic matter in formation of petroleum. AAPG bulletin 58, 499-506, doi: 10.1306/83D90CEB-16C7-11D7-8645000102C1865D, 1974.

Tissot, B.P., Welte, D.H.: Petroleum Formation and Occurrence, 1st ed. Springer, Berlin, 538 pp, 1978.

Transocean, Deepwater Horizon Drills World's Deepest Oil & Gas Well.: September 2. Retrieved June 22, 2018, from: https://web.archive.org/web/20100428004206/http://www.deepwater.com/fw/main/IDeepwater-Horizon-i-Drills-Worlds-Deepest-Oil-and-Gas-Well-419C1.html?LayoutID=6. 2009.

Wang, C. S., Chang, E. Z., & Zhang, S. N.: Potential oil and gas-bearing basins of the Qinghai-Tibetan Plateau, China. International geology review 39, 876–890, doi.org/10.1080/00206819709465307, 1997.

Wang, S., He, L., & Wang, J.: Thermal regime and petroleum systems in Junggar Basin, northwest China. Physics of the Earth and Planetary Interiors, 126(3-4), 237-248, doi:10.1016/S0031-9201(01)00258-8, 2001.

Wang, T. G., Zhong, N. N., Wang, C. J., Zhu, Y. X., Liu, Y., & Song, D. F.: Source beds and oil entrapment-alteration histories of fossil-oil-reservoirs in the Xiamaling formation basal sandstone, Jibei depression. Petroleum Science Bulletin, 01: 24-37, doi:10.3969/j.issn.2096-1693.2016.01.002, 2016.

Wang, Y., Yang, R., Song, M., Lenhardt, N., Wang, X., Zhang, X., Yang, S., Wang, J., & Cao, H.: Characteristics, controls and geological models of hydrocarbon accumulation in the Carboniferous volcanic reservoirs of the Chunfeng Oilfield, Junggar Basin, northwestern China. Marine and Petroleum Geology, 94, 65-79, doi:10.1016/j.marpetgeo.2018.04.001, 2018.

~~White, D. A.: Geologic risking guide for prospects and plays. AAPG Bulletin 77, 2048-2061, doi:10.1306/BDFF8FCE-1718-11D7-8645000102C1865D, 1993.~~

Wu, S. X., Jin, Z. J., Tang, L. J., & Bai, Z. R.: Characteristics of Triassic petroleum systems in the Longmenshan foreland basin, Sichuan province, China. Acta Geologica Sinica-English Edition, 82(3), 554-561, doi:10.1111/j.1755-6724.2008.tb00606.x, 2008.

Xiao, X. M., Zhao, B. Q., Thu, Z. L., Song, Z. G., & Wilkins, R. W. T.: Upper Paleozoic petroleum system, Ordos Basin, China. Marine and Petroleum Geology, 22(8), 945-963, doi:10.1016/j.marpetgeo.2005.04.001, 2005.

Zhou, J., & Pang, X. Q.: A method for calculating the quantity of hydrocarbon generation and expulsion. Petroleum Exploration and Development, 29(1), 24-27, 2002.

Zhou, Y., & Littke, R.: Numerical simulation of the thermal maturation, oil generation and migration in the Songliao Basin, Northeastern China. Marine and Petroleum Geology, 16(8), 771-792, doi:10.1016/S0264-8172(99)00043-4, 1999.

Zhu, C., Hu, S., Qiu, N., Rao, S., & Yuan, Y.: The thermal history of the Sichuan Basin, SW China: Evidence from the deep boreholes. Science China Earth Sciences, 59(1), 70-82, doi:10.1007/s11430-015-5116-4, 2016.

Zhu, D., Liu, Q., Jin, Z., Meng, Q., & Hu, W.: Effects of deep fluids on hydrocarbon generation and accumulation in Chinese petroliferous basins. Acta Geologica Sinica-English Edition, 91(1), 301-319, doi:10.1111/1755-6724.13079, 2017.

Zhu, G., Cao, Y., Yan, L., Yang, H., Sun, C., Zhang, Z., Li, T., & Chen, Y.: Potential and favorable areas of petroleum exploration of ultra-deep marine strata more than 8000 m deep in the Tarim Basin, Northwest China. Journal of Natural Gas Geoscience, 3(6), 321-337, doi:10.1016/j.jnggs.2018.12.002, 2018.

Zhu, Y. M. Coal Mine Geology. China University of Mining and Technology Press, 2011.

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,%.

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

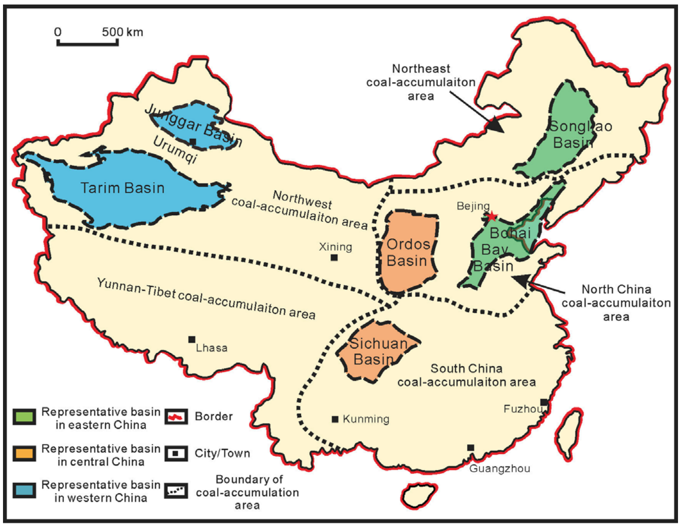

Figure 1: Location of the six representative petroliferous basins and five coal-accumulation areas in China. The studied petroliferous basins, plotted on the China mainland, are pigmented with different colors according to their locations in China. The five coal-accumulation areas, bounded by large geological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

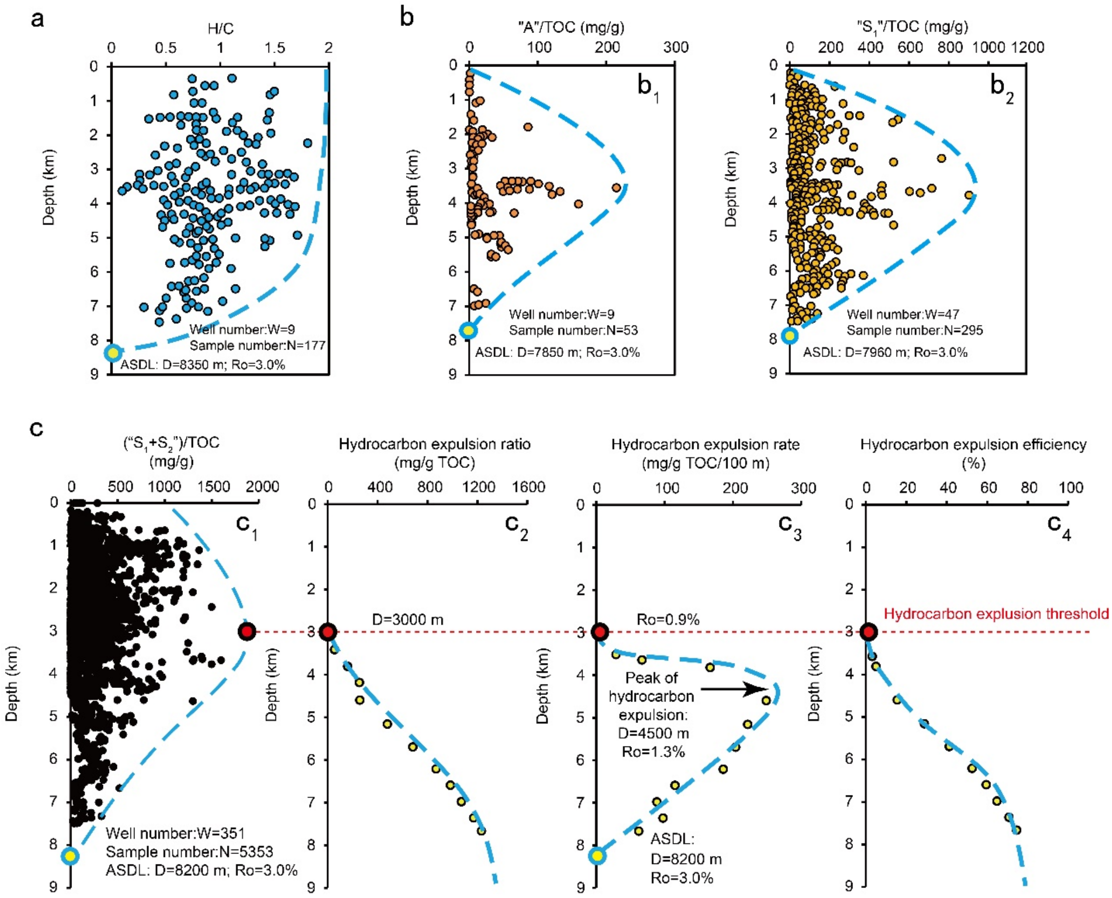

Figure 2: Identification of ASDL in the Junggar Basin using different indicators, including the variation of H/C ratios (a), residual hydrocarbon amounts (b), "$S_1 + S_2$"/TOC (c1), Qe (c2), Ve (c3) and Ke (c4) with depth.

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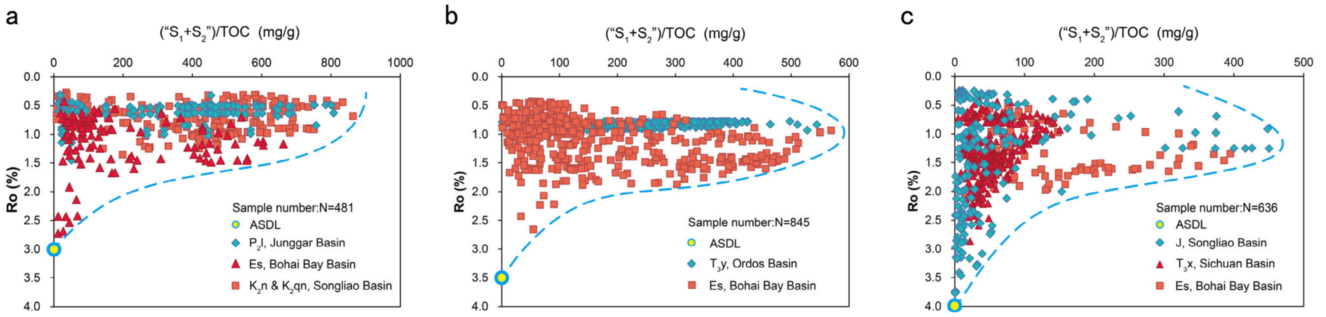


Figure 3: Effects of kerogen types on ASDLs represented by thermal maturity (Ro). From left to right are three plots of hydrocarbon generation potential index versus Ro for source rocks of Type I (a), Type II (b), and Type III (c).

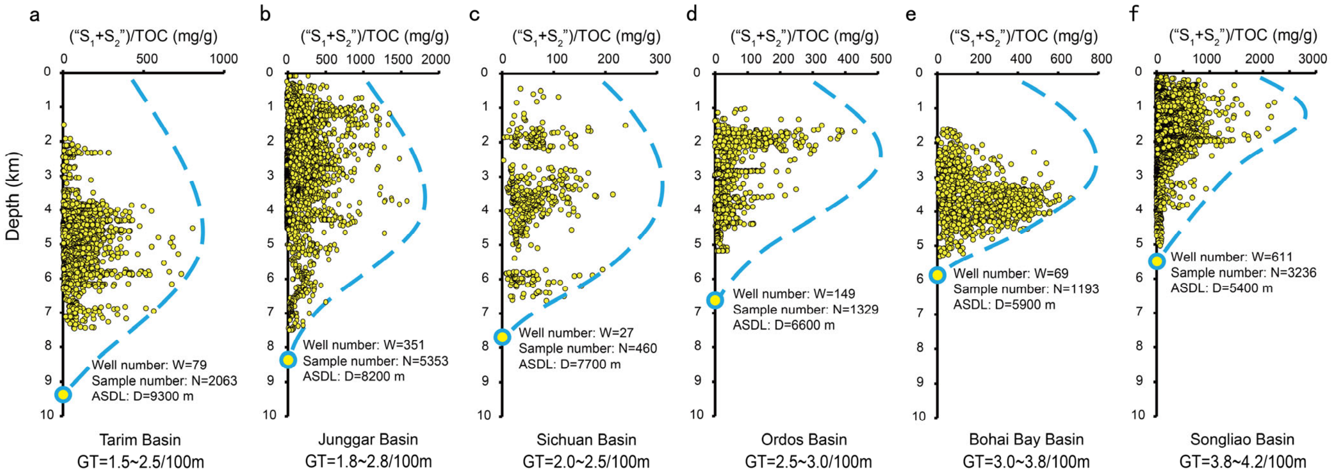


Figure 4: Variation of ASDLs in the six representative basins due to different heat flows. The ASDLs of different petroliferous basins are characterized by hydrocarbon generation potential index (represented by "$S_1 + S_2$"/TOC). From left to right, the heat flow (geothermal gradients) of each basin 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.

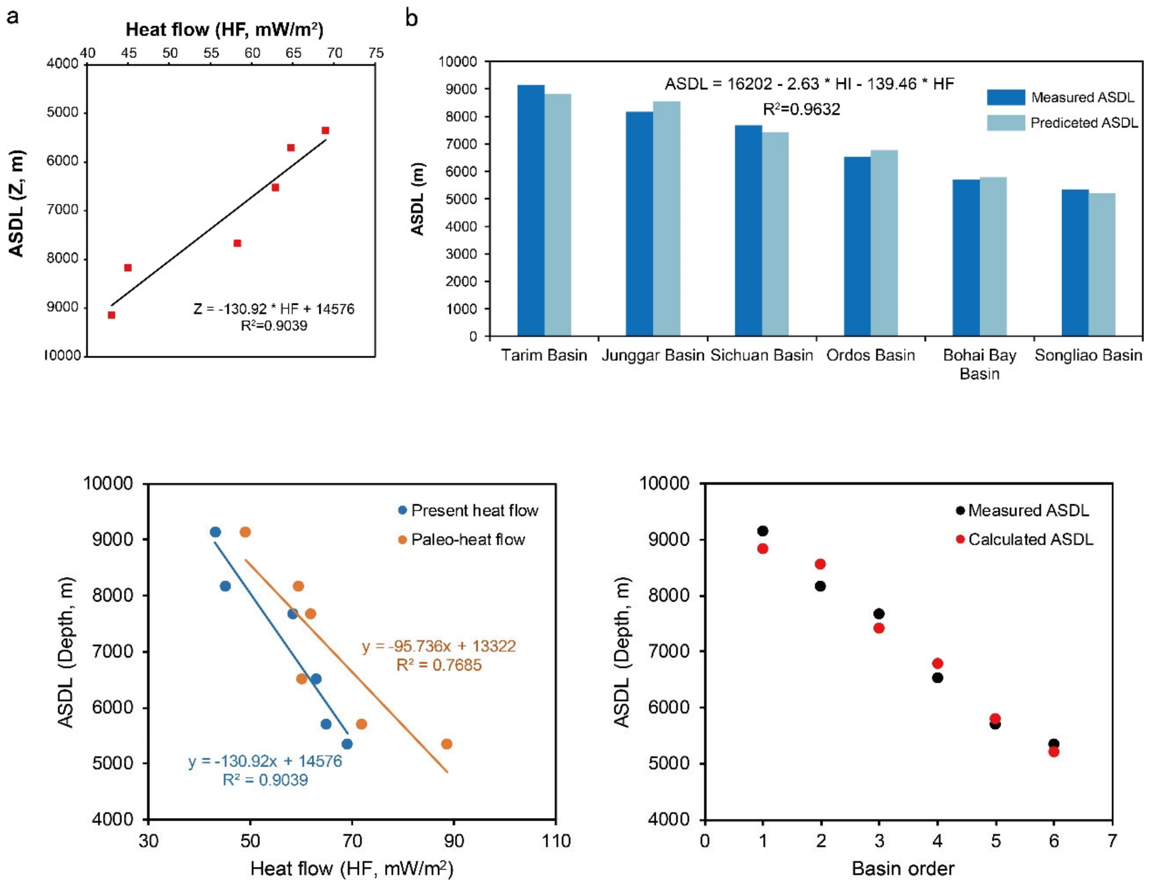


Figure 5: The quantitative relationships among the ASDL, heat flow and kerogen type for the six basins. a, relationship between ASDLs and heat flows. b, the comparison of the modelled depths through Eq. (1) and measured depths of the ASDLs. Basin order: 1. Tarim Basin; 2. Junggar Basin; 3. Sichuan Basin; 4. Ordos Basin; 5. Bohai Bay Basin; 6. Songliao Basin.

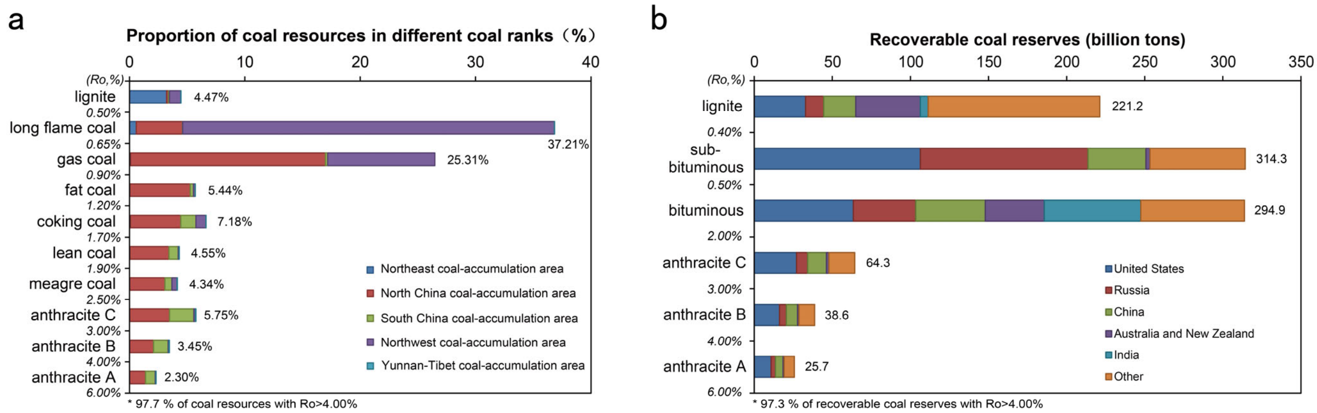
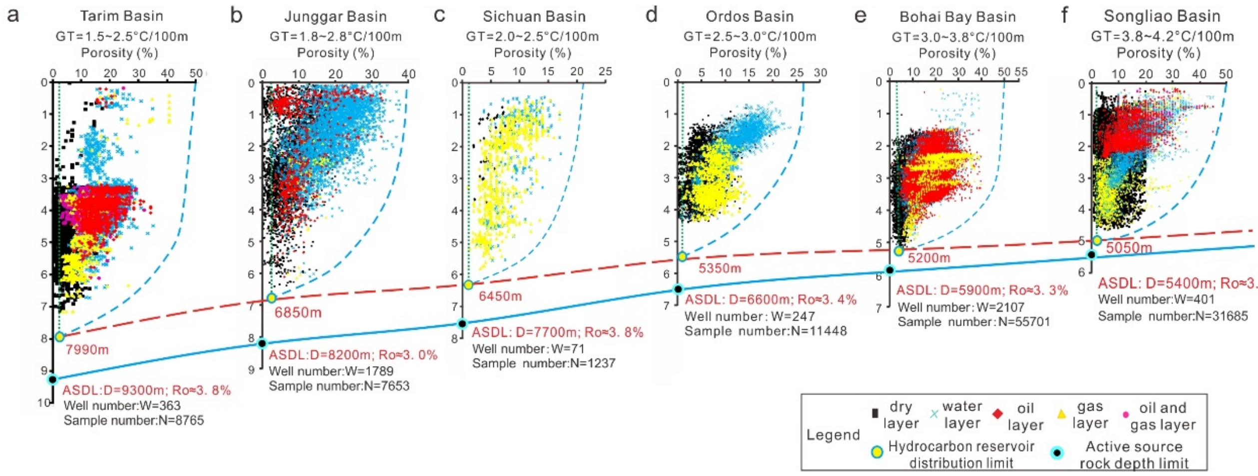


Figure 6: The variation of proved coal reserves with coal ranks in China and in the world. a, the proportion of proved coal reserves with different coal ranks in China (Data from CCRR, 1996; CNACG, 2016). The coal ranks are classified according to the Chinese standard, and the coal accumulation area 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 are projected according to their variation trends.



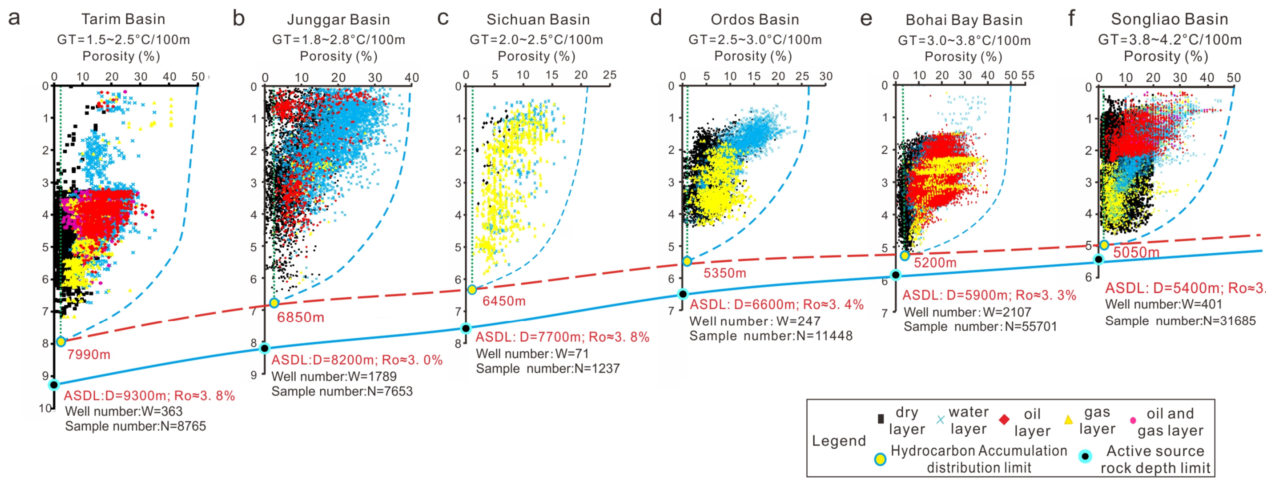
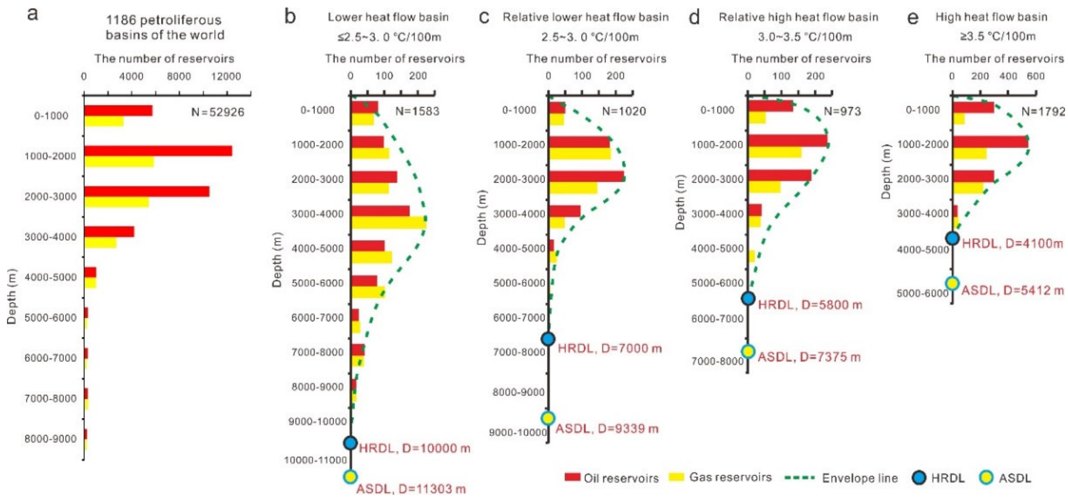


Figure 7: Hydrocarbon drilling results in the six representative petroliferous basins of China to show their relationships with the ASDLs and the HADLs. The results include 116,489 samples of target layers from 4,978 exploration wells in China. The blue dashed line represents the evolution of porosity with depth. Its intercept with the line of 2% porosity marks the HADL. 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 clear that the HADLs are always above the ASDLs.



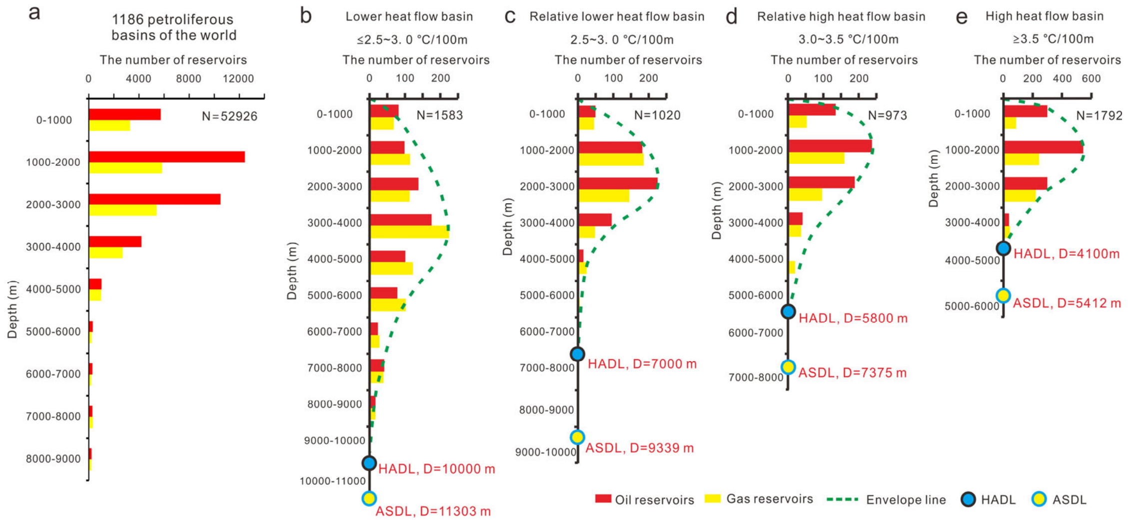


Figure 8: The vertical distribution of numbers of discovered hydrocarbon reservoirs and their relationships with ASDLs and HADLs in the worldwide 1,186 petroliferous basins. a, summation of proven reservoirs in the 1,186 basins. b, low heat flow basins (<25 mW/m^2). c, relative low heat flow basins (25–40 mW/ m^2). d, relative high heat flow basins (40–55 mW/ m^2). e, high heat flow basins (55–70 mW/ m^2). The intercept of the green dashed line on the vertical axis marks the HADL. 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.

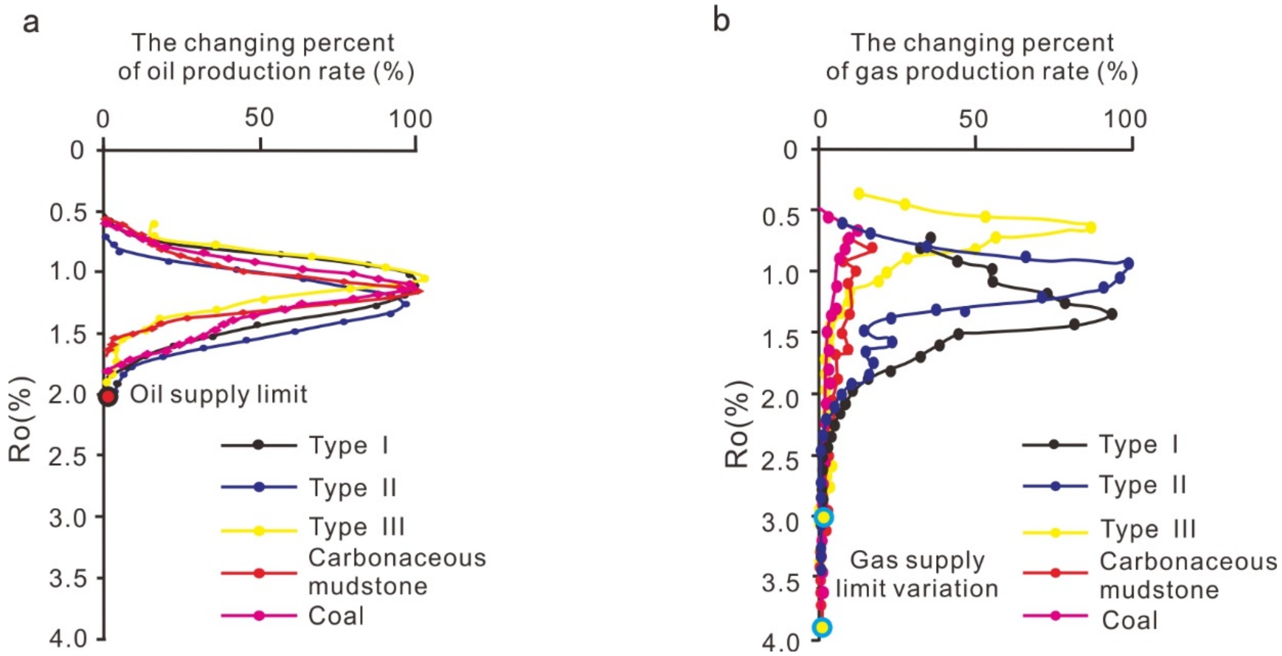


Figure 9: Investigation of ASDLs for different hydrocarbon types by high-temperature and high-pressure pyrolysis simulation. a, the variation of oil production rate with Ro and identification of ASDLo. b, the variation of gas production rate with Ro and identification of ASDLg.

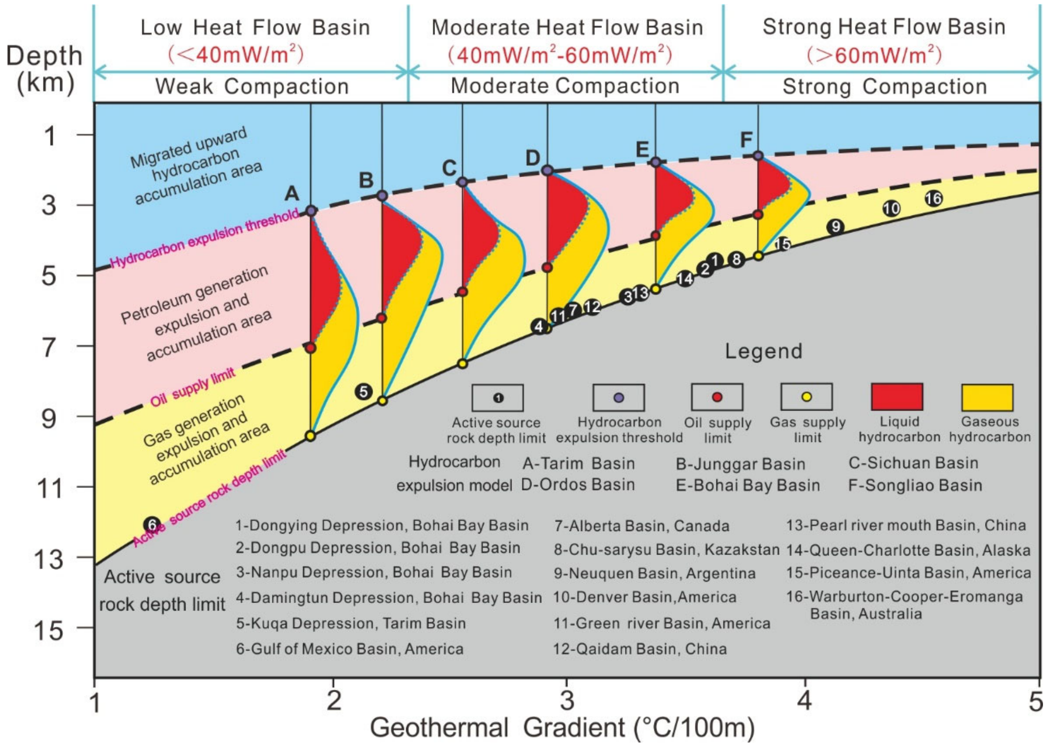


Figure 10: The pattern of ASDLs on the formation and distribution of hydrocarbon reservoirs in petroliferous basins. The upper blue area is favourable for the formation and distribution of conventional oil and gas resources, and hydrocarbons come from the underlying source rocks. The middle pink area is favourable for oil and gas generation, migration, and accumulation from source rocks in this area, mainly form conventional oil/gas reservoirs. The lower yellow area is favourable for natural gas generation, migration, and accumulation from source rocks, mainly form tight unconventional gas reservoirs.