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Mechanisms of inertinite enrichment in Jurassic coals: insights from a Big Data-driven review

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Highlights:

1. Using Big Data methods and thinking to study Jurassic coals that are abnormally enriched in inertinite.
2. Challenging the ‘Less flammable Jurassic’ view through multiple lines of palaeowildfire evidence.
3. Proposing a multifactorial coupled inertinite enrichment mechanism.

4. Establishing enrichment models corresponding to hot-summer humid continental and monsoon-influenced climates.

Abstract: Big Data-driven research is thriving in the geosciences, with initiatives such as The Deep-Time Digital Earth (DDE) program (<https://deep-time.org/>), which is a “big science program” by the International Union of Geological Sciences (IUGS). Northern and northwestern Chinese environments produced a significant number of typically inertinite-rich coals during the Jurassic, which have been extensively researched and represent a high-quality subject for Big Data-driven studies. Inertinite in coals are widely accepted and applied as direct evidence of palaeowildfire with important palaeoclimatic significance, but the enrichment mechanism of inertinite in Jurassic coals have not yet been comprehensively understood. In this research, Big Data methodology and thinking were used to collect 1,298 sources of information with inertinite content, and to reconstruct the palaeogeographic distributions of that inertinite. In addition, more than 300 datasets on polycyclic aromatic hydrocarbons (PAHs) and inertinite reflectance were collected. Based on these data and in combination with palaeoclimatic databases, two enrichment mechanisms for the high levels of inertinite are proposed. The results show that Jurassic coals in China are significantly enriched in inertinite compared to coals in the rest of the world, with an average inertinite content of 18.9% in the Early Jurassic and up to 36.8% in the Middle Jurassic. Combustion-sourced PAHs are widespread in Jurassic coal seams in different basins and are dominated by 4-ring and 5-ring PAHs. Both coal petrology and PAHs characteristics are indicative of a wildfire origin for inertinite, and the inertinite reflectances suggest that the palaeowildfire types were mainly low-temperature fires. It is proposed that the abundant inertinites in Jurassic coals were formed as the result of the multi-factorial coupling of palaeoflora, palaeoclimates, and palaeoenvironmental evolution. The enrichment models for the inertinite in the Early-Middle Jurassic coals indicate that

these inertinites were mainly formed during periods of more obvious seasonal contrasts. Based on analysis from a Big Data review of inertinite concentrations in coals, a quantitative classification criterion is proposed to define those with > 30% inertinite as “inertinite-rich coal”, and those with > 50% inertinite as “inertinite coal”.

Keywords: Big Data, Jurassic, Inertinite-rich coal, Palaeowildfire, Palaeoclimate

1. Introduction

An accepted definition of “inertinite-rich coals” has not been uniformly or quantitatively determined from past studies. [Harvey and Dillon \(1985\)](#) defined coal with an inertinite content higher than 16% as “inertinite-rich coal” when studying maceral distributions in Carboniferous coal seams from Illinois, USA. In contrast, [Li \(2005\)](#) defined coal with an inertinite content greater than 30%, and vitrinite/inertinite ≤ 2 , as “inertinite-rich coal” when studying the coal macerals in the Shendong mining area of the Ordos Basin, China. Globally, the most typically inertinite-rich coals are “Gondwana coals” from the Gondwana palaeo-continent, which are now found in Australia, India and South Africa and can contain up to 100% inertinite (vol.%, mmf–mineral matter free) ([Diessel, 2010](#); [Hower et al., 2012](#)).

Jurassic coal deposits are extensively developed in northern and northwestern China in the area north of the Kunlun, Qinling, and Dabie mountains in China that includes the Ordos, Junggar, Tuha, Yili, and Qaidam basins with some containing significant amounts of inertinite ([Dai et al., 2015](#); [Zhang et al., 2020](#); [Hou et al., 2022](#); [Xie et al., 2022](#); [Du et al., 2024](#); [Han et al., 2024](#)). These have not previously been systematically evaluated to assess how their inertinite levels vary, which deposits can be assigned as “inertinite rich”, and what processes led to the inertinite enrichment.

There are long-standing views on the possible different origins of macerals within the inertinite ([ICCP System 1994](#); [Shao et al., 2024](#)). [Hudspith and Belcher \(2020\)](#) argued that some semifusinite in coal may have formed during diagenesis,

while [Hower et al. \(2011\)](#) noted that a limited number of macerals, including macrinite, were formed by microbiological processes and derived from non-plant material. [O'Keefe et al. \(2013\)](#) suggested the possibility of non-wildfire oxidative processes to form fusinite and semifusinite, while [Scott \(2000, 2010\)](#) and [Glasspool et al. \(2015\)](#) argued that inertinite is formed almost exclusively as a product of palaeowildfires. Observations on modern charcoal deposits and experimental charring studies of plant materials strongly support the view that inertinite is a product of palaeowildfires ([Jones et al., 1991](#); [Jones, 1997](#); [Scott and Glasspool, 2005](#)). As a consequence, the inertinite group has been widely used as direct evidence for palaeowildfire ([Glasspool et al., 2015](#); [Baker, 2021](#); [Hou et al., 2022](#); [Sun, 2024](#)), including studies of materials interpreted as fossil charcoal or fusain in sedimentary rocks. In essence, 'inertinite' is defined by its chemical and microscopical properties (ICCP, 1994), whereas the name 'fusain' is assigned based on the assumed palaeowildfire mode of formation.

Wildfire has been a fundamental occurrence on Earth since the Silurian ([Glasspool and Gastaldo, 2022](#)). It has shaped ecosystems, and in recent times has made headlines worldwide for its impacts on environments, ecosystems and people ([Kroll et al., 2023](#)). The levels of wildfire activity are influenced by a combination of factors including climate, vegetation, and atmospheric compositions ([Scott, 2000](#)). Compelling evidence points to palaeowildfires increasing in frequency and intensity across vulnerable ecosystems as the impacts of climate change grow more evident ([Pellegrini et al., 2021](#)). Therefore, the characteristics of wildfires can be considered within specific climatic and environmental contexts. In this study, to minimise the effects of environmental variation, the properties of inertinite in coals formed in comparable Jurassic coal-forming settings from different times and places were reviewed to make our interpretations more internally consistent and comparable.

The Jurassic did not have permanent ice caps in either hemisphere and was a greenhouse period with frequent climate fluctuations ([Scotese et al., 2021](#)). The Jurassic global mean surface temperature was 5–10 °C higher than that of modern pre-

industrial times ([Li et al., 2022](#)); while Jurassic atmospheric carbon dioxide levels reached more than 1,000 ppm, which is two to three times that of the present-day ([Foster et al., 2017](#)). The study of deep-time wildfires can help improve our understanding of modern wildfire regimes, and their relationships, nature and frequency with global climatic change.

Inertinite macerals such as fusinite and semifusinite give an indication of the magnitude, frequency, and type of palaeowildfires, based on their compositional percentage against other associated coal macerals and their reflectance (R_{oil}) ([Jones, 1997](#); [Scott, 2000](#)). Because of the strong correlation between wildfires and atmospheric oxygen content, variations in the occurrence and abundance of inertinite in the Earth's history have been used to estimate pO_2 contents ([Glasspool et al., 2015](#); [Hou et al., 2022](#); [Xu et al., 2022](#)). Polycyclic aromatic hydrocarbons (PAHs) with more than four rings serve as reliable biomarkers for palaeowildfires and may provide additional evidence in palaeowildfire research ([Yunker et al., 2002](#); [Karp et al., 2020](#); [Fox et al., 2022](#)). The development of palaeoclimate databases ([Scotese et al., 2021](#); [Li et al., 2022](#); [Hu et al., 2023](#)) and palaeoatmospheric composition prediction models ([Foster et al., 2017](#); [Mills et al., 2023](#)) have provided opportunities for quantitative studies of feedback systems between palaeowildfire activity and diverse factors in ecosystems.

In recent years, there has been an increasing number of studies undertaken on Jurassic palaeowildfires ([Marynowski and Simoneit, 2009](#); [Petersen and Lindstrom, 2012](#); [Wang et al., 2020](#); [Xu et al., 2020](#); [Zhang et al., 2020](#); [Hollaar et al., 2021](#); [Hou et al., 2022](#); [Xie et al., 2022](#); [Han et al., 2024](#)). These studies provide ample data and empirical evidence to investigate the mechanisms of inertinite enrichment in Jurassic coals.

The “Big Data” approach (Fig. 1) has added a new and innovative method of research to understand and explore in detail existing data sets ([Zhou et al., 2018](#); [Vance et al., 2024](#)). The term “Big Data” does not refer to the size of the data set, but to all the data covering a phenomenon ([Mayer-Schonberger et al., 2013](#)). The key lies

in the innovation of thinking, in the use of Big Data methods, and in the adoption of data-driven models (Jiao et al., 2023). “Big Data” works alongside traditional methods of research, and indeed is dependent on this previous work for the sources of data; however, it requires a shift in intrinsic thinking, and willingness to explore new research methods (Zhai et al., 2018; Jiao et al., 2023). The Deep-Time Digital Earth (DDE) program is the first “big science program” initiated by the International Union of Geological Sciences (IUGS) (Wang et al., 2021), and provides an opportunity for data-driven geoscientific research.

Numerous examples of palaeowildfires in the Jurassic coal basins of northern and northwestern China have been studied, focusing on the evidence for palaeowildfires, palaeowildfire types, and the reconstruction of atmospheric oxygen levels (Xu et al., 2020; Zhang et al., 2020; Hou et al., 2022; Xie et al., 2022; Han et al., 2024). There are also some studies on the formation mechanisms of inertinite-rich coal in the Jurassic (Li, 2005; Wang et al., 2020). However, most of these studies have focused on a particular coal basin and as such are limited in their focus to palaeowildfire events rather than exploring deeper relationships of widespread palaeowildfires to factors such as palaeoclimatic conditions and palaeofloral characteristics.

To explore the contribution of palaeowildfires to inertinite formation in different climatic backgrounds and their role in palaeoecosystems, this study uses Big Data methods to collect, review and analyse information on inertinite macerals, inertinite reflectance, PAHs, palaeoflora and the inferred palaeoclimates of the Jurassic coal-forming environments in northern and northwestern China. Based on these investigations, data including palaeowildfire fossil records, types and locations of palaeowildfires, estimations of the palaeoatmospheric oxygen contents in the Early-Middle Jurassic, and the roles of palaeoclimate, palaeoflora, pO_2 , and pCO_2 in the enrichment of the inertinite in Jurassic coals were identified. The outputs provide a relatively holistic perspective on the causes of abundant inertinite in Jurassic coals and shows the potential of Big Data-driven research in the geosciences.

2. Geological setting

The study area of this paper lies to the north of the Kunlun, Qinling and Dabie mountains in China, and comprises three main regions of Jurassic peat formation: northern China, northwestern China, and northeastern China (Fig. 2). Within these regions, the data comes mainly from northwestern and northern China, with less data available from northeastern China (Fig. 2). During the Jurassic, the global continental plate configuration was composed of the Laurasia and Gondwana landmasses (Scotese and Wright, 2018). The Early-Middle Jurassic coals mainly developed in the warm temperate and boreo-tropical regions of Laurasia and in the coastal regions of Gondwana (Boucot et al., 2013). In the Early-Middle Jurassic, the study areas were located on the eastern edge of Laurasia, and mainly comprising the Tarim Plate and the North China Plate (Scotese and Wright, 2018).

In these study areas, the Jurassic strata are continental facies that record terrestrial ecosystem successions (Deng et al., 2017). The area was dominated by a series of non-marine intermontane cratonic basins, typified by the Tarim, Junggar, and Qaidam basins in northwestern China and the Ordos Basin in northern China (Li et al., 2004). In addition relatively small cratonic basins occurred in northwestern China including the Tuha, Santanghu, Yili and Hexizoulang basins (Fig. 2) (Deng et al., 2003; Li et al., 2004). In northern and northeastern China, some small rift basins were developed, including the Datong, Jibei (northern Hebei), Jingxi (western Beijing), and Beipiao basins (Fig. 2) (Deng et al., 2003; Li et al., 2004).

Jurassic strata in the study areas, from the bottom upwards, are composed of two separate sets of sedimentary facies (Zhang et al., 1998). The lower set is the coal-bearing strata of the Early Jurassic to lower Middle Jurassic, developed in a humid palaeoclimate. The upper set consists of variegated sandstones and red beds of the upper Middle Jurassic to Upper Jurassic, which developed under a semi-arid to arid palaeoclimate (Deng et al., 2003) (Fig. 3). The Early-Middle Jurassic was the stratigraphic interval with the most intensive coal accumulation in China, especially

the lower part of the Middle Jurassic which contains the most abundant coal resources (Fig. 3). The main coal-bearing strata include the Badaowan, Xishanyao, Xiaomeigou, Dameigou and Yan'an Formations ([Zhang et al., 1998](#)) (Fig. 3).

3. Materials and methods

In this Big Data study, a total of 1,298 inertinite maceral compositional identifications, 283 inertinite reflectance values, and 65 PAHs analyses of Jurassic coals in northern and northwestern China were collected from published literature and unpublished degree theses from the China National Knowledge Infrastructure (CNKI) and Web of Science databases. The data of inertinite maceral contents in coal and inertinite reflectance are in the form of percentage values, and the PAHs analyses included the types of PAH compounds and their concentrations (ug/g coal) or relative percentages of each component. Results of coal macerals (vol.%, mmf-mineral matter free i.e. I+V+L=100%) and inertinite reflectance are given in Table S1, and PAHs data are given in Table S2.

From the climate simulation dataset of [Li et al. \(2022\)](#), which has several modelling parameters, only the surface temperature (T; unit: °C) and precipitation (P; unit: mm month⁻¹) values were used in this study. Geographical distribution of the T and P data have the dimensions of 55 (simulation) × 12 (month) × 192 (latitude) × 288 (longitude). The simulation number 36 corresponds to the Sinemurian age (c. 190 Ma) and the palaeogeographic ranges (around 40–60°N, 80–100°E) correspond to the main coal accumulation areas in northwestern China. Simulation number 38 corresponds to the Aalenian-Bajocian age (c. 170 Ma) and the palaeogeographic ranges (around 30–50°N, 80–130°E) correspond to the main coal accumulation areas in northwestern and northern China (Table S3). The values are in raster data format, of which a total of 48 raster files of temperature and precipitation for each month were exported from the network Common Data Form (netCDF) database (<https://www.unidata.ucar.edu/software/netcdf/>) NetCDF has been developed by the Unidata project of the University Corporation for Atmospheric Research (UCAR) to

record the characteristics of scientific data and is a standard for describing, encoding and sharing array-type data.

GeoDeepShovel (<https://deep-time.org/tools>), an online platform for data extraction from scientific literature with AI assistance (Zhang et al., 2023), was used in this research to extract data from PDF documents and build a scientific database (Shao et al., 2024). From the literature GeoDeepShovel accumulates data containing meta-information including information from tables, texts, and locations included in analysis.

A limited portion of the evaluated literature provided accurate location information for samples, so location information for the remaining sample points was obtained through a coordinate query system based on the geographic location described in the text. From the present day geographic locations palaeo-coordinates were converted using Gplates (version 2.4.0; www.gplates.org), a software package providing reconstructions of geological and palaeogeographic features through geological time (Scotese and Wright, 2018).

ArcGIS Pro (2.8.6) was used to generate visualizations, conduct advanced mapping analytics, and for projecting average inertinite content onto palaeoplate maps for palaeogeographic recovery. This software was also used to visualize raster files of palaeoclimate simulation data and overlay them with the inertinite palaeogeographic maps.

In addition to data collection and analysis, some samples were collected in this study to observe the macroscopic and microscopic characteristics of inertinite (Shao et al., 2024). Sampling locations are shown in Fig. 2. The coal samples were prepared as polished epoxy-bound pellets which were observed under a ZEISS Axio Scope.A1 microscope. For observation of homogenized cell walls, small inertinite fragments were mounted on a standard stub, coated with gold, and then observed under a ZEISS Gemini 300 Scanning Electron Microscope (SEM).

4. Results

4.1. Distribution of inertinite in Jurassic coal

[Diessel \(2010\)](#) recorded the percentages of inertinite in coals from various regions of the globe during different geological time periods, and indicated that most Jurassic coals have inertinite contents below 25% with an average inertinite content of 12.9%. This study provides a large amount of new Chinese data to the [Diessel \(2010\)](#) research, and shows that inertinite in Jurassic coal seams in China is abnormally enriched compared with other time periods (Fig. 4a), varying from 0.2–97.7% and having an average value of 32.5%.

Palaeogeographical reconstruction of the inertinite data was undertaken on a 10 Ma time bins interval. The inertinite values are distributed in the Early Jurassic Sinemurian stage which correspond to the deposition of the Badaowan Formation and its temporal equivalents, and the Middle Jurassic Aalenian-Bajocian stages which correspond with the Xishanyao Formation and its temporal equivalents (see Fig. 3). The Early Jurassic data are mainly distributed in northwestern China (Fig. 5a), with a total of 308 data points, accounting for 23.7% of the total data, and an average content of inertinite in coal of 18.9%. Middle Jurassic coal accumulation was more intense, and the corresponding inertinite data were more abundant, occurring across most of northern and northwestern China (Fig. 5b), with a total of 990 data points, accounting for 76.3% of the total data, with significantly higher inertinite content and an average of 36.8%.

4.2. Vitrinite and inertinite reflectance

The coal samples inertinite reflectance data are summarized from the open literature (7 papers, 283 samples), covering the Ordos, Junggar, and Qaidam basins in Table 1. The inertinite reflectance values from the Ordos Basin in the Dongsheng coalfield range from 0.66%–1.49% (avg. 0.99%) ([Zhang et al., 2020](#)), the Binchang coalfield range from 0.74%–3.06% (avg. 1.83%) ([Wang et al., 2020](#); [Han et al.,](#)

2024), and the Yushen coalfield range from 0.70%–2.0% (avg. 1.77%) (Xu et al., 2020). In the Qaidam Basin, inertinite reflectance values from the Yuqia coalfield range from 0.71%–1.47% (avg. 1.27%) (Xie et al., 2022). From the Taxihe coal mine in the southern Junggar Basin, inertinite reflectance values range from 1.69%–5.15% (avg. 2.75%) (Hou et al., 2022), while from the Wucaiwan coal mine in the eastern Junggar Basin values range from 0.72%–3.17% (avg. 1.24%) (Yang et al., 2022). The results show that inertinite reflectance in the southern Junggar Basin is high, while the other basins have only sporadic high values, and the average inertinite reflectance value is lower than 3% (Table S1).

Vitrinite reflectance data for the coal seams are also summarized from the open literature (4 papers, 91 samples), covering the Ordos, Junggar, and Qaidam basins in Table 1. The average vitrinite reflectance values vary from 0.52%–0.74% in the three basins.

4.3. PAHs compounds and ratios

The PAHs data is summarized from the open literature (6 papers, 76 samples) covering the 64 coals in the Ordos, Junggar, Qaidam and Santanghu basins and 12 coal measures mudstones in the Tarim basin in Table 2. The major PAHs compounds identified in all samples include: Naphthalene (Nap), Fluorene (Flu), Phenanthrene (Phe), Anthracene (Ant), Fluoranthene (Fla), Pyrene (Pyr), Benzo(a)anthracene (BaA), Chrysene (Chr), Benzo(j)fluoranthene (BjF), Benzo(b)fluoranthene (BbF), Benzo(k)fluoranthene (BkF), Benzo(a)pyrene (BaP), Indeno(1,2,3-cd)pyrene (InPy), Dibenzo(a,h)anthracene (DahA), and Benzo(g,h,i)perylene (BghiP) (Table S2).

Because of the differences in PAHs testing methods and equipment in samples from different regions, the relative abundance varies greatly, so the data in this paper are converted to the ratios of different components for comparison. The PAHs compositions of the samples from all regions are dominated by the 3-5 ring components (Table 2). This paper selects multiple ratios to make judgements about the sources of PAHs, namely: Fla / (Fla + Pyr), BaA / (BaA + Chr) and InPy / (InPy +

BghiP) (Yunker et al., 2002). Additionally, a ratio of low molecular weight PAHs / Total PAHs is used to infer smoke vs. char/burn residue input (Fox et al., 2022).

5. Discussion

5.1. Wildfires in the Early and Middle Jurassic

5.1.1. Quantitative classification of the inertinite-rich coal

Based on the acquisition of a significant amount of inertinite data from Jurassic coal in China (Fig. 4a and Fig. 5), combined with the global coal inertinite database (Shao et al., 2024), an analysis of the abundance of inertinite in Jurassic coals in China and worldwide was undertaken. Analysis of inertinite composition values showed a median value of 21.9% and an upper quartile of 47.7% for the global Jurassic data, and a higher median of 27.6% and a higher upper quartile value of 52.3% for the Jurassic data in China (Fig. 6; Table S1). These results show that Chinese Jurassic coals are enriched in inertinite compared to coals in other regions of the world.

The global and Chinese Jurassic data were linked together in a series (concatenated) set, and the median and upper quartile of the Chinese Jurassic data were used as boundaries to classify inertinite-rich coals. Based on outputs the values were rounded down to the nearest 10 %, so that when the inertinite content equals or exceeds the median quartile value of 30 % it is defined as “inertinite-rich coal”, and when the inertinite content exceeds the upper quartile value of 50 %, it is defined as “inertinite coal”. This resolves the ambiguity in the definition of inertinite-rich coal noted in the opening sentences of the introduction and provides comparable, quantitatively defined definitions for future studies.

5.1.2. Petrographic evidence of palaeowildfires

Inertinite provides valuable information on palaeowildfires (Scott, 2000). Observations on modern charcoal deposits and experimental charring studies indicate

that inertinites, especially fusinite and semifusinite, are formed almost exclusively as a product of palaeowildfires (Jones, 1997; Scott and Glasspool, 2007). It has been suggested that some semifusinite may have been formed by degradation (O'Keefe et al., 2013) or diagenesis (Hudspith and Belcher, 2020) of plant tissues. The Jurassic coals in the study area are low-rank brown coals with mostly around 0.5% vitrinite reflectance (Ye et al., 1998), whereas the reflectance of semifusinites is significantly higher than that of the accompanying vitrinite group (Fig. 7 h-i); this suggests that the semifusinite is more likely to be of palaeowildfire origin. Many particles of inertodetrinite are relics from palaeowildfires in or around the peatland that have been transported into the coal-forming environments (ICCP, 2001).

Abundant fossil charcoal (inertinite) particles with sizes ranging from several microns to several centimeters were observed in hand specimens, in reflected light microscopy, and under the SEM (Fig. 7 and 8). These macroscopic and microscopic features are consistent with the characteristics of fossil charcoal described by other scholars (Scott, 2010; Xu et al., 2020). 407 data sets have empirically detailed maceral compositions within the inertinite, with the average ratio percentage of (fusinite + semifusinite + inertodetrinite) vs. (inertinite) at 91.4%. Any error introduced by the inclusion of a small proportion of the inertinite interpreted as non-combustion is therefore considered comparatively negligible (Diessel, 2010). Consequently, in this paper, the inertinite is used as coal petrological evidence for palaeowildfires. In the study area, the average inertinite content in Early and Middle Jurassic coal seams reaches 18.9 % and 36.8 %, respectively. The inertinite contents of the Middle Jurassic coals are significantly higher than those in the Early Jurassic coals (Fig. 4a). This observation provides evidence supporting the interpretation of elevated levels of palaeowildfires during the Middle Jurassic coal accumulation interval in the study areas. The vertical variation of inertinite abundances elucidated in this study (Fig. 4a) indicates that palaeowildfires were widespread and frequent in northern and northwestern China during the Middle Jurassic. In the Early Jurassic, the

lower inertinite content indicates that palaeowildfires may not have been as widespread during coal accumulation as those of the Middle Jurassic.

5.1.3. PAHs evidence of palaeowildfires

In sedimentary strata PAHs originate from either incomplete combustion or degradation of organic matter by microorganisms during diagenesis (Zakir Hossain et al., 2013). Potentially combustion-derived PAHs mainly consist of 3–6 ring PAHs, which are distinguished by high abundances of unsubstituted compounds (Denis et al., 2012). The greater numbers of aromatic rings tend to be associated with stronger preservation capacities (Denis et al., 2012). Low aqueous solubility hinders biodegradation of PAHs with four or more rings (Lima et al., 2005), thus PAHs with four or more rings are reliable biomarkers of palaeowildfire (Xiao et al., 2020). While some researchers have used ratios of 5/3-ringed PAHs and (6 and 7)/3-ringed PAHs to reflect the combustion temperatures of palaeowildfires (Kaiho et al., 2020; Fox et al., 2022), Karp et al. (2020) pointed out that after modern burning experiments PAH molecular distributions can reflect both plant sources and the burning phase, but not burn temperatures. Therefore, PAHs need to be used with caution as biomarkers of palaeowildfire, and tracing their sources is essential.

PAH ratios used in modern analogues to determine petrogenic (i.e., oil/coal-related) vs. pyrogenic (fire) origins for PAHs were successfully applied in palaeo PAH studies to show pyrogenic origins for PAHs (Fox et al., 2022). Generally, $Fla / (Fla + Pyr) > 0.5$ is considered to be a typical characteristic for combustion sources, while $Fla / (Fla + Pyr) < 0.4$ indicates petrogenic source, and $0.4 < Fla / (Fla + Pyr) < 0.5$ indicates a mixed source with combustion and petrogenic substances (Yunker et al., 2002). The ratios of $BaA / (BaA + Chr)$ for petrogenic and combustion inputs are < 0.2 and > 0.35 , respectively. Accordingly, the ratios of $InPy / (InPy + BghiP)$ for petrogenic and combustion inputs are < 0.2 and > 0.5 , respectively (Yunker et al., 2002). These ratios, averaged over the samples from various basins, are indicative of PAHs as a source of palaeowildfire (Table 2). The results show that a mixed

pyrogenic origin for samples from the Qaidam Basin and the Dongsheng coalfield in the Ordos Basin cannot be entirely ruled out as ratios of Fla / (Fla + Pyr) plot mostly as mixed sources and ratios of InPy / (InPy + BghiP) also show mixed sources but are overall closer to pyrogenic origins (Fig. 9; Table S2). The PAHs ratios are indicative of palaeowildfire sources in most samples from the other basins or regions investigated (Fig. 9).

Smaller PAH compounds have higher vapor pressures and are preferentially emitted with the gaseous phase during biomass combustion, while larger PAH compounds have lower aqueous solubility and tend to partition more strongly into organic coatings and particles (Lima et al., 2005). Additionally, the ratio of the potentially combustion-derived PAHs is used to infer smoke vs. char or burn residue input since combustion. Smoke can travel a great distance from the burn source (up to ~10,000 km), whereas char or burn residue is typically deposited closer to the source and travels a relatively shorter distance (up to ~10 km) (Fox et al., 2022). The ratios greater than ~0.75–0.8 imply predominantly smoke input whereas below ~0.75–0.8 imply predominant char/burn residue input (Karp et al., 2020). The results of this study show that this ratio is below 0.75 except for the Tuha Basin, indicating that palaeowildfire products are predominantly char or burn residue input (Table 2).

Evidence from PAHs and coal petrology suggest that palaeowildfires were frequent in northern and northwestern China during the Early-Middle Jurassic, especially the Middle Jurassic. Combined with reports of Jurassic palaeowildfires from other regions of the globe (Marynowski et al., 2011; Zakrzewski et al., 2020; Hollaar et al., 2021), the high level of the inertinite contents demonstrate that palaeowildfires were possibly globally widespread at that time.

5.1.4. Palaeowildfire types inferred from inertinite reflectance

Modern experimental and wildfire charcoal R_o measurements have demonstrated that high reflectance is largely the result of increasing heating temperatures during combustion (Jones, 1997; Scott and Glasspool, 2007). Jones (1997) expressed the

correlation between reflectance value and temperature as a linear regression equation $T=184.10+117.6\times R_o$ ($R^2=0.91$) in which T is the combustion temperature ($^{\circ}\text{C}$), R_o is the random reflectance of inertinite under oil immersion (%), and R^2 is the correlation coefficient for the experimental data. Using this formula, it is possible to assess not only the burn temperature but also infer the type of wildfire.

Wildfires can be grouped into three basic types based on different burning temperatures, namely, ground fires, surface fires and crown fires (Jones et al., 1991). Ground fires burn organic material below the litter layer and generally reach maximum temperatures around $400\text{ }^{\circ}\text{C}$; Surface fires burn litter, herbaceous and shrubby plants and can reach higher temperatures than ground fires up to around $650\text{ }^{\circ}\text{C}$; In contrast, crown fires typically burn canopies of trees and larger shrubs, producing intense heat with temperatures of $800\text{ }^{\circ}\text{C}$ or higher (Brown et al., 2012; Shao et al., 2024).

The overall low inertinite reflectance in the samples from different Jurassic coal basins in northern and northwestern China, mostly concentrated between 0.7% and 2.0%, indicates that the type of palaeowildfires at that time were dominated by low-temperature fires represented by surface and ground fires (Table 1).

The products of low-temperature fires are mainly mesoscopic and macroscopic charcoal $<180\text{ }\mu\text{m}$ (Scott, 2000). The Big Data analysis shows that much of the inertinite in coals is meso- and macroscopic (Fig. 7), which corroborates that the Jurassic environments in the study areas were dominated by surface and ground fires.

5.2. Palaeoatmospheric oxygen levels estimated from inertinite contents

Glasspool et al. (2015) compiled a large database of the inertinite contents of coals from different geological periods, and then proposed an inertinite to $p\text{O}_2$ calibration curve. In this study, the inertinite Big Data were imported into the model of Glasspool et al. (2015) to calculate the atmospheric oxygen content was

approximately 24.2% in the Early Jurassic and 26.4% in the Middle Jurassic. It should be noted that this model is only applicable when there is sufficient data available, and that values from individual coal seams in single basins may be an exception, and therefore not representative of a general indicator such as atmospheric oxygen content.

The Krause model of Jurassic palaeoatmospheric oxygen prediction has been revised from 20% (Krause et al., 2018) to around 25% (Mills et al., 2023) after incorporating feedback from palaeowildfires, which is in broad agreement with the reconstructed palaeoatmospheric oxygen content shown here derived from the inertinite content (Fig. 4d).

Belcher and McElwain (2008) suggested that the lower pO_2 limit for combustion should be 15%, but for the wildfire to widely spread required pO_2 18.5% (Belcher et al., 2010). Atmospheric oxygen levels in the Early and Middle Jurassic reached around 25%, sufficient to support the spread of wildfires. He and Lamont (2018) advocated that climate acts as a more significant control than O_2 on the occurrence of wildfire during periods of low atmospheric O_2 . However, when the atmospheric oxygen content exceeds 18.5%, as previous studies and our results show, in the Early-Middle Jurassic, then the oxygen levels may not have had such a significant influence on wildfires as O_2 levels was already sufficient to support combustion. The other factors controlling wildfire types, frequency and severity include the vegetation and climate in a high oxygen atmosphere (Baker et al., 2019), with specific factors including amounts of precipitation, temperature range, and seasonality control on vegetation providing suitable and sufficient combustible fuel.

5.3. Role of botany and climate on inertinite enrichment in Jurassic coal

5.3.1. Floral provision of sufficient and sustained wildfire fuel

The flora of the Mesozoic was dominated by ‘filicalean’ ferns and gymnosperms (Cycadopsida, Ginkgopsida, Czekanowskiales and Coniferopsida), with both Cycadopsida and Ginkgopsida reaching their peak during the Jurassic (Vakhrameev, 1991). In the Middle Jurassic flora of northwestern China, ferns accounted for ~36%, Ginkgopsida ~24%, Cycadopsida ~16%, and Coniferopsida ~10% (Fig. 2) (Zhang et al., 1998; Zhong et al., 2003). The fronds of Cycadales can reach up to 1.5 m long (Sun et al., 2016), and through ontogeny old leaves are pushed downwards by the growth of new leaves, and are shed and then fall to the ground. Mesozoic *Ginkgo* fossils are common and abundant in coal-bearing strata, and are sometimes seen in large numbers along levees and show seasonal leaf concentrations through defoliation (Wang et al., 1997). Mesozoic conifers have a similar ecology to extant conifers and also have a seasonal concentrations of shed leaves (Deng, 2007). These littered piles of desiccated branches and leaves would have provided sufficient fuel for surface and ground fires, as well as providing targets for lightning strikes and wildfire ignition.

The atmospheric CO₂ concentrations in the Jurassic reached more than 1000 ppm (Fig. 4c) (Foster et al., 2017), with a concentration of 1320 ppm inferred from Middle Jurassic *Ginkgoites* fossils in northwestern China (Wu et al., 2016). Rising atmospheric CO₂ concentrations can increase photosynthetic capacity, above-ground biomass production, and primary productivity of plant communities (Ainsworth and Long, 2005). The vast majority of Jurassic land plants were C₃ species (Sage, 2004), which were more sensitive to high levels of CO₂ than C₄ plants that had not fully evolved, therefore photosynthesis in the C₃ plants during the Jurassic was more responsive to elevated CO₂ with resulting greater productivity (Ainsworth and Long, 2005). Therefore, high CO₂ concentrations in the Jurassic contributed to terrestrial

plants flourishing, that in turn may have provided increased amounts of fuel for palaeowildfires.

Biological studies of modern forest wildfires have shown that frequent and low-severity wildfires can be necessary to maintain species diversity in forests, rather than destroying plant populations ([Kroll et al., 2023](#)). This feedback relationship between frequent, low-severity wildfires and forest ecology may also have existed in the Jurassic. The major Jurassic plant groups are believed to have had their own characteristics to defend against or adapt to low-severity palaeowildfires ([Van Konijnenburg-Van Cittert, 2002](#); [Korasidis et al., 2019](#)).

Ferns were the dominant herbaceous plants during most of the Mesozoic, including in the Mesozoic open conifer forests ([Van Konijnenburg-Van Cittert, 2002](#)). Some of these species have been preserved mainly or only as fusain, indicating not only that palaeowildfires had occurred relatively frequently at that time but also that ferns grew in fire-prone environments ([Van Konijnenburg-Van Cittert, 2002](#)).

The vascular bundles in trunks of the Cycadales are rich in starch, and the coralline roots are symbiotic with cyanobacteria, which have a strong nitrogen-fixing capacity. Their stem cortex and pith have mucilaginous tracts and store a large amount of water and nutrients. These characteristics make the Cycadales trunks highly stress-resistant, allowing them to survive low-severity palaeowildfires and recover within a few months after burning ([Zhu et al., 2012](#)).

Ginkgoales trees may have exceptionally long lifetimes, with some modern trees living up to a thousand years. The tree *Ginkgo biloba* generally belongs to the upper storey in forest communities, and has thick stems and high crowns ([Zhou et al., 2020](#)). [Wang et al. \(2020\)](#) considered that the vascular cambium in *Ginkgo* can retain the capacity for continuous growth for hundreds of years or even millennia, and the tree can continue to synthesize substances such as lignin for a long time in order to increase the density and strength of the trunk, which in turn increases its resistance to stresses such as unfavorable environmental factors. Ginkgoales can be unaffected by

low-severity palaeowildfires, whereas dead trunks produce more charcoal when charred due to their exceedingly high lignin content.

Today, boreal forests are dominated by coniferous species with thick bark and sparse lower branches that can constrain crown fires (He and Lamont, 2018). Trees from these conifer families were present in low-mid latitudes in the Jurassic including our study area and may have acted in a similar way (Deng, 2007). The fire-protective behavior of these major plant populations can have positive feedback with palaeowildfires and sustainably provide fuel for frequent ground and surface palaeowildfires.

5.3.2. Different climates lead to different wildfire regimes

The main coal accumulation areas in the Early Jurassic (c. 190 Ma) were around 40–60°N and 80–100°E. These areas had a mean annual temperature of ~1°C and a mean annual precipitation of ~877 mm (Fig. 10a); considered a cool and humid climate, with inconspicuous seasonal differences in precipitation and large differences in temperature (Li et al., 2022). The main coal accumulation areas in the Middle Jurassic (c. 170 Ma) were around 30–50°N and 80–130°E. These areas had a mean annual temperature of ~10.7°C and a mean annual precipitation of ~581 mm, considered a warm-temperate humid climate. These areas had four strongly distinct seasons with winter (December-February) monthly mean temperatures of ~-8.1°C and precipitation of ~74.1 mm, with summer (June-August) monthly mean temperatures of ~28.9°C in summer and total summer precipitation around 216.6 mm (Li et al., 2022) (Fig. 10b).

The Köppen climate classification provides an efficient way to describe climatic conditions defined by multiple variables and their seasonality with a single metric (Chen and Chen, 2013). With reference to Köppen climate classification scheme (Kottek et al., 2006; Peel et al., 2007), the climate type of the Early Jurassic in the study area was a hot-summer humid continental climate (climate symbol: Dfa), while the climate type of the Middle Jurassic in the study area was a Monsoon-influenced

hot-summer humid continental climate (climate symbol: Dwa). The monsoon influence on the study area is also supported by palaeoclimate simulations from [Hu et al. \(2023\)](#).

Palaeoflora characteristics ([Deng et al., 2017](#)) and palaeoclimate databases ([Li et al., 2022](#)) indicate a palaeoclimate with four distinct seasons in northern and northwestern China during the Early-Middle Jurassic (Fig. 10). The annual mean temperature at that time was 5–10°C higher than today ([Scotese et al., 2021](#)) (Fig. 4b). Lightning frequency displays a positive response to surface temperature ([Price, 2013](#)), so it is likely that Early-Middle Jurassic lightning frequencies were higher than today, and as the predominant ignition source would have led to frequent and widespread palaeowildfires.

The Early Jurassic has few records of inertinite and its inertinite content in coals were significantly lower than those of the Middle Jurassic, which is closely related to the palaeoclimate at that time. Northwestern China in the Early Jurassic had mean annual temperature 10°C cooler but mean annual precipitation was 300 mm more than those of the Middle Jurassic, and seasonal contrasts were not significant. In terms of impact the palaeoclimatic change on palaeowildfire, the rainfall is considered to be the most critical factor, since rainwater would wet the fuels and reduce their flammability ([Wotton et al., 2017](#)). Thus, the relatively cool and rainy palaeoclimate of the Early Jurassic would have been less prone to the occurrence of palaeowildfires (Fig. 10a, Fig. 11).

Inertinite was abundant in Middle Jurassic coals in northern and northwestern China and its average content in coals reached over 35%. The palaeoclimate at that time was characterized by elevated temperatures but moderate rainfall, and there were clear seasonal contrasts, with rainfall and heat at the same season ([Bao and Hu, 2024](#)) (Fig. 10b, Fig. 12). Although the climate was humid, [Flannigan et al. \(2015\)](#) demonstrated that seasonal precipitation increases associated with climate change must be in the order of 15% to offset every 1°C rise in temperature. At that time, the average monthly summer temperature in the study area reached 28.9°C, which could

result in regional dry spells leading to widespread palaeowildfires and the production of vast quantities of charcoal.

5.3.3. Feedback mechanisms between factors in palaeoecosystems

[Miao \(2006\)](#) summarized the palaeoecological distributional characteristics of major plant populations by analyzing the palaeoclimate sensitivity and fossil preservation of different plants in the Middle Jurassic of the Junggar Basin. The plains between rivers and swamps or their surrounding slopes and hills were the principal areas of vegetation at that time. Ferns and *Czekanowskia* grew closest to water bodies, with *Ginkgo* close to the water body and conifers including Pinaceae further away (Fig. 13).

The rate of carbonization, the ratio of charred to uncharred wood, depends on the moisture content of fuel, and is associated with drought severity ([Trabaud, 1976](#)). If the fuel is very dry, complete combustion (burning to ash) would be intense, resulting in a large amount of ash and gaseous emissions, and thus the production of charred particles would be proportionally low ([Carcaillet et al., 2002](#)).

It has been observed that, for a given atmospheric composition, a fuel moisture content (denoted M_{ex}) exists above which the fuel would not support a spreading flame. [Watson and Lovelock \(2013\)](#) established a formula for the relationship between M_{ex} and atmospheric oxygen content: $M_{ex} = 8O_2 - 128$, where M_{ex} is in percent of dry weight and O_2 is the oxygen percent concentration. Using this formula, and an atmospheric oxygen content in the Middle Jurassic of 26.4%, a M_{ex} of about 83% represents the fuel moisture content that would have been required to inhibit wildfires. The elevated temperatures of the Middle Jurassic resulted in fuels drying out easily (Fig. 4b), and this would be accompanied by higher lightening frequencies which could trigger frequent and widespread palaeowildfires. Although the rate of charcoalification was not very high in the Middle Jurassic, a larger biomass volume would produce more charcoal during combustion (Fig. 12a). With an atmospheric oxygen of 24.2% in the Early Jurassic, a M_{ex} (fuel moisture content) of about 64%

would have been required to minimise wildfires. The study area had sufficient rainfall in the Early Jurassic that would have increased fuel moisture (Fig. 10a), limiting wildfire activity and ultimately resulting in lower inertinite contents (Fig. 13b).

The conditions that make wildfires extinguish under natural conditions include lack of oxygen and fuel, or rainfall ([Lenton, 2013](#)). As northern and northwestern China had adequate atmospheric oxygen levels of ~25% during the Early-Middle Jurassic, this did not restrict wildfires. The types of palaeowildfires in the study area were dominated by surface and ground fires, and such low-severity palaeowildfires were not likely to cause large-scale plant mortality ([Scott, 2000](#)). At the time, the study area was heavily vegetated ([Deng, 2007](#)) and could recover quickly after low-severity palaeowildfires ([Scott, 2000](#)), so there was no or very little risk of fuel scarcity. The factor that has the highest probability of a wildfire being extinguished is rainfall, other than natural barriers such as water bodies or areas previously denuded of vegetation (fire breaks).

Frequent climate fluctuations in the Jurassic ([Scotese et al., 2021](#)) and the contrasting seasons during the Middle Jurassic ([Li et al., 2022](#)) may have allowed mires to temporarily dry out so that the uppermost part, above the water table, could have been affected by surface fires. Furthermore, because the Jurassic was a typical greenhouse climate period, high surface temperatures ([Scotese et al., 2021](#)) and the frequency of lightning ([Price, 2013](#)) would have triggered wildfires in forests frequently, resulting in charcoal from wildfires outside of mires washing into the peat forming environment. In addition, the coal seams themselves may have been subject to natural wildfire activity due to tectonic uplift and erosional exposure of the seams ([Stracher and Taylor, 2004](#)).

Mires and flood plains are favorable sinks for charcoal ([Baker et al., 2019](#)), which requires rainfall and surface flow (run-off) for transportation during the accumulation processes (e.g., [Scott, 2010](#)). Charcoal in sediments is probable evidence left behind by surface water flow transportation processes (Fig. 8 f, g). The transported charcoal

that was deposited in coal-forming environments would therefore be classified as inertinite, contributing towards an enrichment of inertinite in the resulting coal seams.

5.4. Jurassic vs. Cretaceous “firehouse world” inertinite values in coals

Previous research has considered that the Cretaceous was a “fire-prone world” by studying the characteristics of inertinite in coals and mudstones (Wang et al., 2021; Xu et al., 2022). Brown et al. (2012) collected global records of Cretaceous charcoal and demonstrated that terrestrial sediments preserved abundant charcoal. Combined with globally high temperatures and high atmospheric O₂ levels (Fig. 4b and 4c), these conditions made the Cretaceous one of the most fire-prone periods in the Earth’s history (He and Lamont, 2018).

Based on previous analyses of global inertinite databases, it could be assumed that the low levels of inertinite during the Jurassic period (Diessel, 2010; Glasspool and Scott, 2010) and the low Jurassic oxygen concentrations predicted in some models (Berner, 2009; Krause et al., 2018) would suggest that the Jurassic was a less flammable period in the Earth history than the Cretaceous (He and Lamont, 2018). The Jurassic was also a typical greenhouse climate period (Scotese et al., 2021), with high temperatures and high levels of atmospheric oxygen content (Fig. 4b and 4c). The results show that, in the study areas, inertinite abundance during the Jurassic was higher than in the Cretaceous (Fig. 4a) within coals. As a result, Jurassic palaeowildfires may be analogous to Cretaceous palaeowildfire regimes and as frequent. The presented evidences challenge the “less flammable Jurassic” view (He and Lamont, 2018), and supports the Jurassic also being a fire-prone world.

6. Conclusions

(1) Based on quantitative analysis of global Jurassic coals, those with inertinite > 30% are defined as “inertinite-rich coals” and coals with inertinite > 50% are defined as “inertinite coals”. In northern and northwestern China, the average content of

inertinite in Early Jurassic coals reaches 18.9%, and in Middle Jurassic coals is higher and reaches up to 36.8%. Middle Jurassic coals in China are typically inertinite-rich coals.

(2) Potentially combustion-derived PAHs are widely present in coals in various Early and Middle Jurassic basins in northern and northwestern China. Together these lines of evidence support widespread occurrence of palaeowildfires in the Early and Middle Jurassic of northern and northwestern China and challenge the “less flammable Jurassic” view that has been previously postulated. The Early-Middle Jurassic was also a fire-prone stratigraphic interval.

(3) The atmospheric oxygen content reconstructed from the inertinite Big Data is ~24.2% in the Early Jurassic and rises to ~26.4% in the Middle Jurassic. These atmospheric oxygen concentrations were sufficient to create favorable atmospheric conditions for extensive palaeowildfire activity. Comparison of the atmospheric oxygen values from inertinite broadly agree with values from the latest atmospheric concentration models and demonstrate the validity of atmospheric oxygen prediction from inertinite content.

(4) The formation of inertinite in Early to Middle Jurassic coals in northern and northwestern China is the result of multifactorial coupling of palaeoflora, palaeoclimatic and palaeoenvironmental factors, and the enrichment of inertinite was mainly caused by frequent but low severity palaeowildfires, mainly formed during a time with climates of marked seasonal contrasts in temperature and precipitation.

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Tables

Table 1. Vitrinite reflectance and wildfire temperatures inferred from inertinite reflectance in Middle Jurassic of northern and northwestern China.

Study area	Vitrinite reflectance ($R_{o,max}$ %)	Inertinite reflectance (%)		Wildfire temperature (°C)	References
	Average	Range	Average		
Dongsheng, Ordos Basin		0.66–1.49	0.99	261.8–359.6	(Zhang et al., 2020)
Binchang, Ordos Basin	0.63	0.74–3.06	1.83	271.2–544.4	(Wang et al., 2020; Han et al., 2024)
Yushen, Ordos Basin	0.52	0.70–2.0	1.77	266.5–419.6	(Xu et al., 2020)
Qaidam Basin	0.56	0.32–3.89	1.27	221.8–642.2	(Xie et al., 2022)
Southern Junggar Basin	0.74	1.69–5.15	2.75	383.1–790.6	(Hou et al., 2022)
Eastern Junggar Basin		0.72–3.17	1.24	258.9–557.4	(Yang et al., 2022)

Table 2. Compounds and ratios of PAHs in coals of different regions.

PAH	Ratios and Interpretation		Referen ce	Concentration of the PAHs (ug/g coal)				Junggar Basin	Qaidam Basin	Santang hu Basin
				Yushen mining area, Ordos Basin	Dongshen g mining area, Ordos Basin	Binchang mining area, Ordos Basin	Tarim Basin			
Percentage of different ring PAH	3-ringed/Total			6.64	8.48	16.46		29.42	6.63	4
	4-ringed/Total			25.39	25.59	18.74		23.99	29.31	43.7
	5-ringed/Total			13.58	45.78	36.12		28.98	44.77	21.08
PCD (%)	6+7-ringed/Total			2.46	20.15	24.23		13.02	17.9	2.14
Source of PAH PCD	Fla/(Fla+P yr)	> 0.5 = pyrogenic/primary < 0.5 = petrogenic/degraded	(Yunker et al., 2002)	0.59	0.48	0.56	0.59	0.51	0.38	0.67
	BaA/(BaA +Chr)	> 0.35 = pyrogenic 0.2–0.35 = mixed source < 0.2 = petrogenic		0.53	0.6	0.59	-	0.57	0.46	0.57
	InPy/ (InPy +BghiP)	> 0.2 = pyrogenic < 0.2 = petrogenic		0.58	0.34	0.5	0.30	0.57	0.47	0.61
Smoke vs. char/bur n residue	LMW/Tot al	> ~0.75–0.8 = smoke < ~0.75–0.8 = burn/char residue	(Karp et al., 2020)	0.51	0.26	0.24		0.28	0.27	0.39

Reference	(Xu et al., 2020)	(Zhang et al., 2020)	(Han et al., 2024)	(Qiu et al., 2023)	(Yang et al., 2022)	(Xie et al., 2022)	(Xu et al., 2020)
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LMW, Low molecular weight PAHs, include (Phenanthrene + Anthracene + Fluoranthene + Pyrene); PAH_{PCD}, potentially combustion-derived PAHs; Fla, Fluoranthene; Pyr, Pyrene; BaA, Benzo(a)anthracene; Chr, Chrysene; InPy, Indeno(1,2,3-*cd*) pyrene; BghiP, Benzo (g, h, i) perylene.

Figure captions

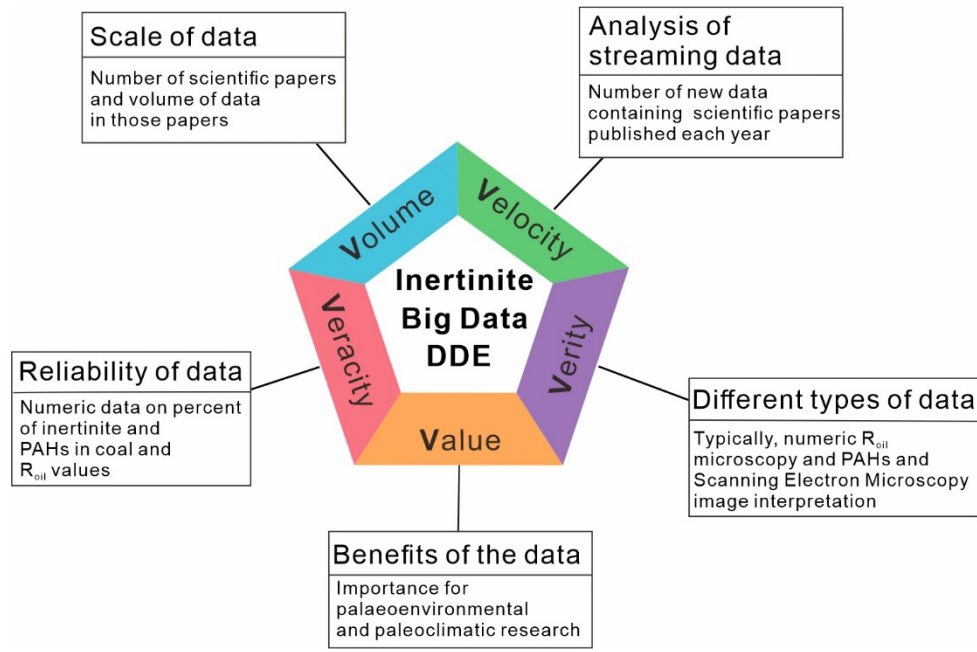


Fig. 1. The five V's of Big Data analysis as applied to Jurassic inertinite research

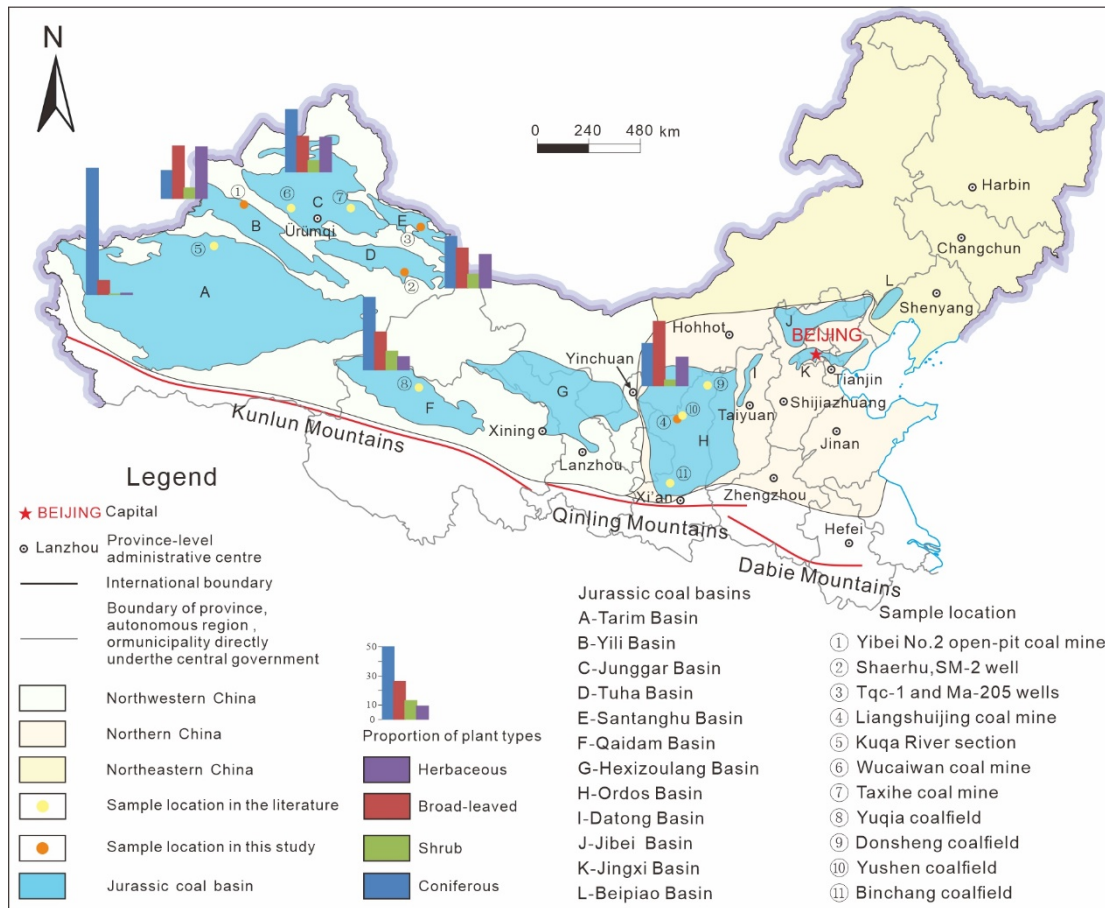


Fig. 2 Distribution of Jurassic coal basins and coal-forming vegetation, and sample location in northern China. Coal basins location and range from Shao et al. (2020), palaeoflora data from Zhong et al. (2003), China map after <http://bzdt.ch.mnr.gov.cn/>, Regional division of China.

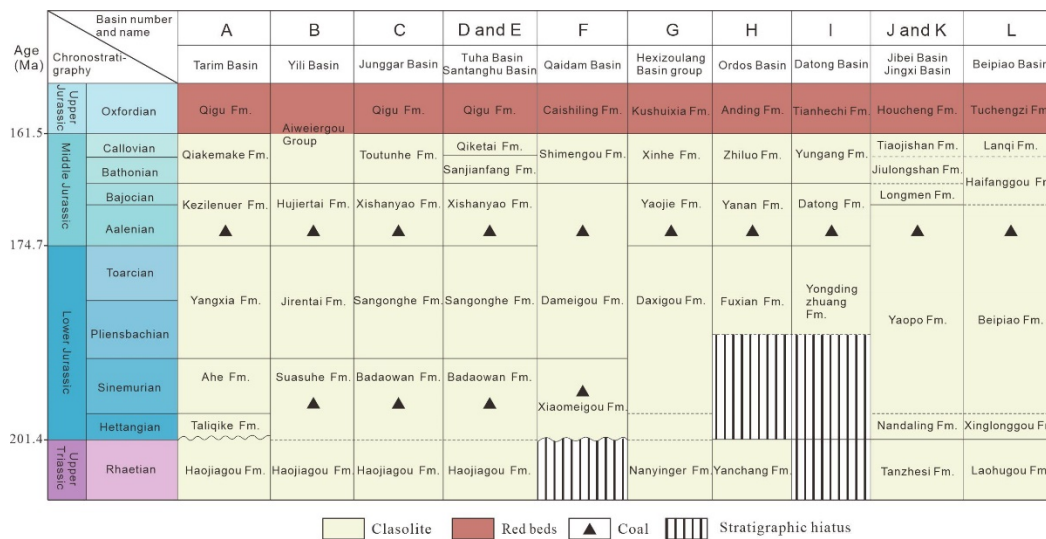


Fig. 3 Jurassic lithostratigraphic correlation chart of northern China regions (CCS, 2018).

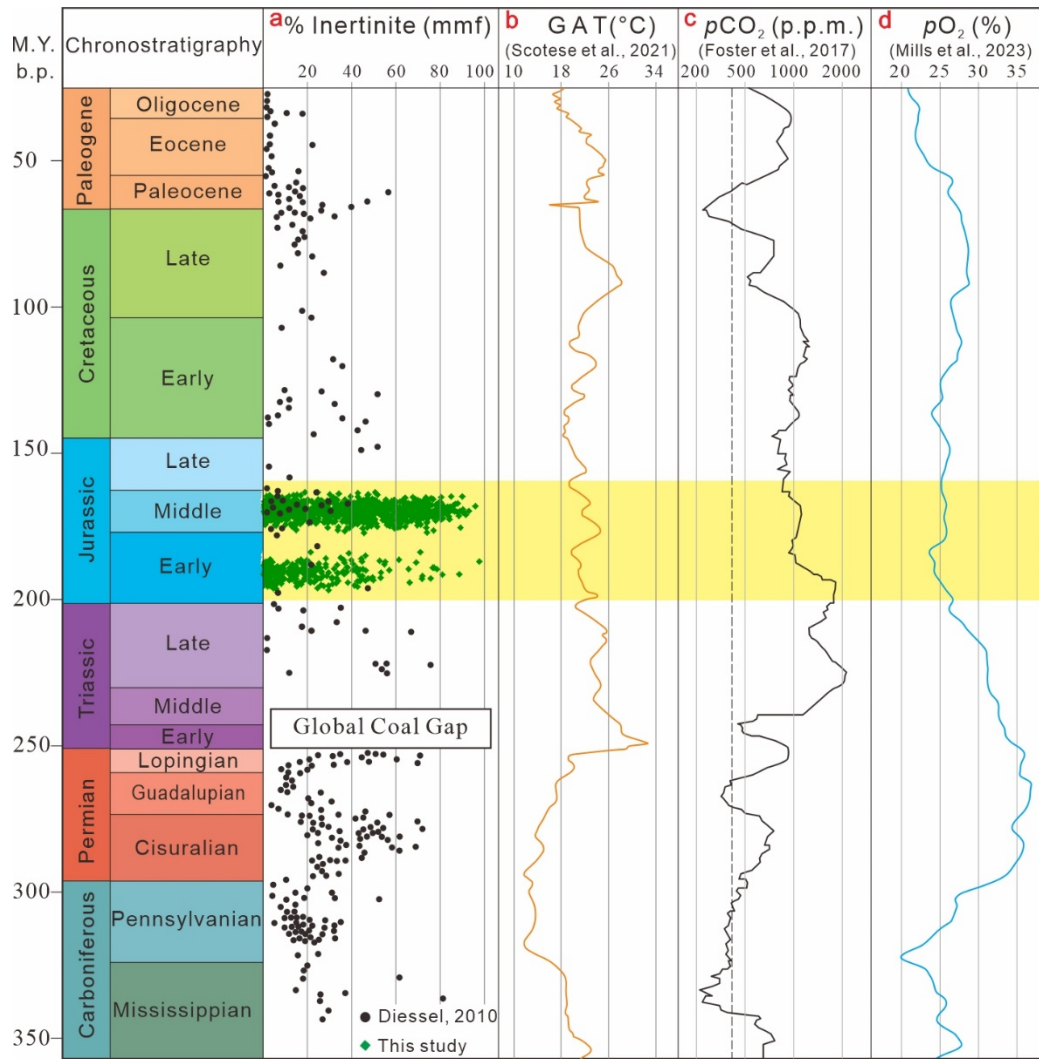


Fig. 4. Changes of inertinite and palaeoclimatic indicators in geological history. a. Inertinite abundances revised after [Diessel \(2010\)](#); b. Palaeotemperature data from [Scotese et al. \(2021\)](#); c. Palaeo $p\text{CO}_2$ data from [Foster et al. \(2017\)](#), the black dotted line represents global atmospheric CO_2 concentration in 2023, data from World Meteorological [Organization \(2023\)](#); d. Palaeo $p\text{O}_2$ data from [Mills et al. \(2023\)](#).

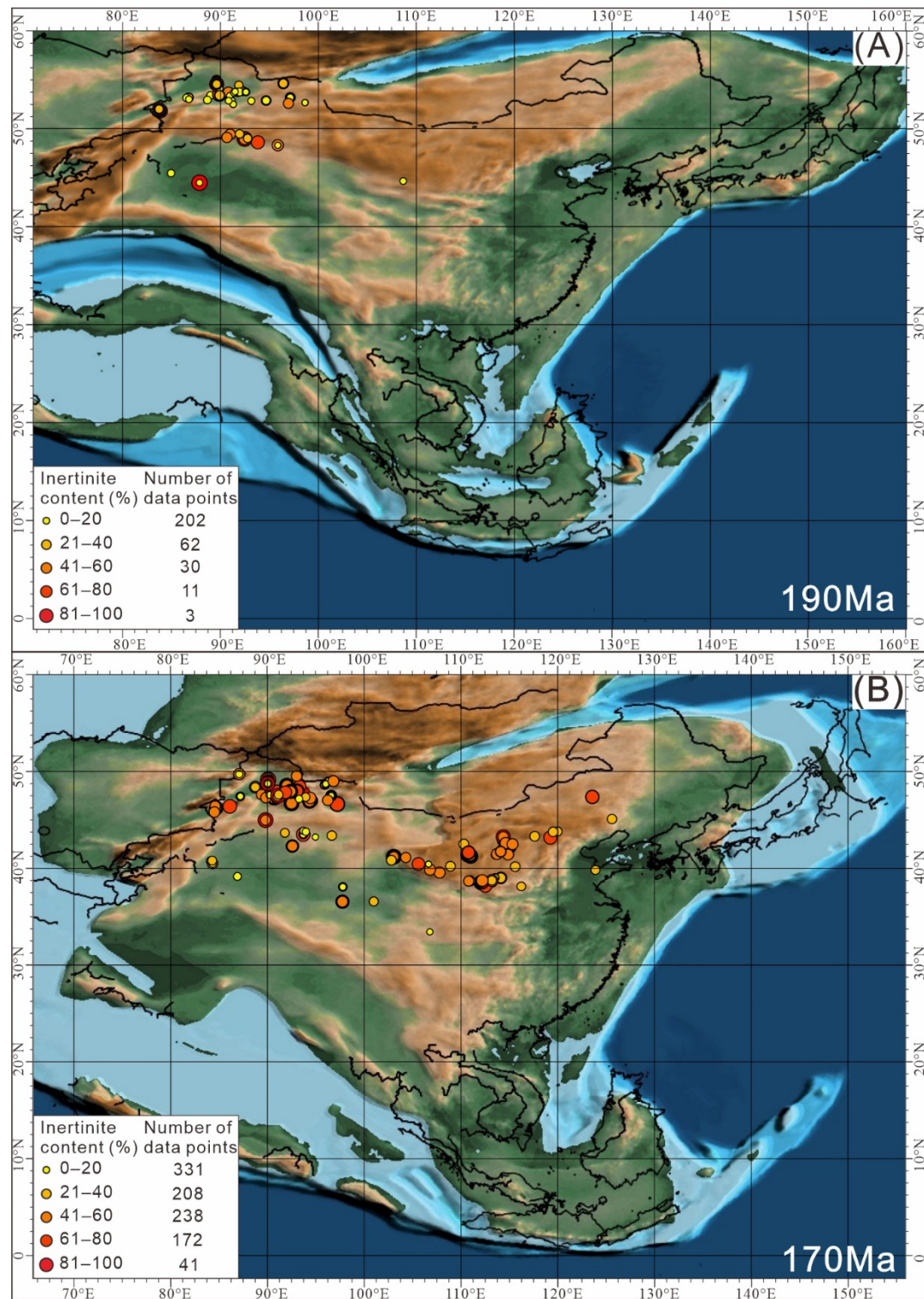


Fig. 5. Geographic distribution of wildfire evidence in the Early Jurassic (Sinemurian ~ 190 Ma) and the Middle Jurassic (Aalenian-Bajocian ~ 170 Ma). Plate reconstructions from [Scotese and Wright \(2018\)](#). Numbers in brackets refer to the amount of data points.

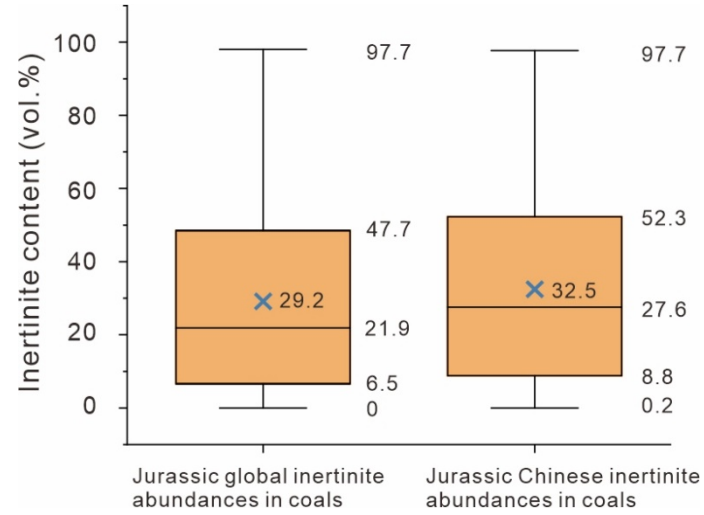


Fig. 6. Box plot of Jurassic global and Chinese inertinite abundances in coals. Data from [Shao et al. \(2024\)](#). Lower bar = minimum value, upper bar = maximum value, x = average, lower horizontal line in box = bottom quartile (25%), middle horizontal line in box = median, upper horizontal line in box = upper quartile (75%), black squares represent data outliers.

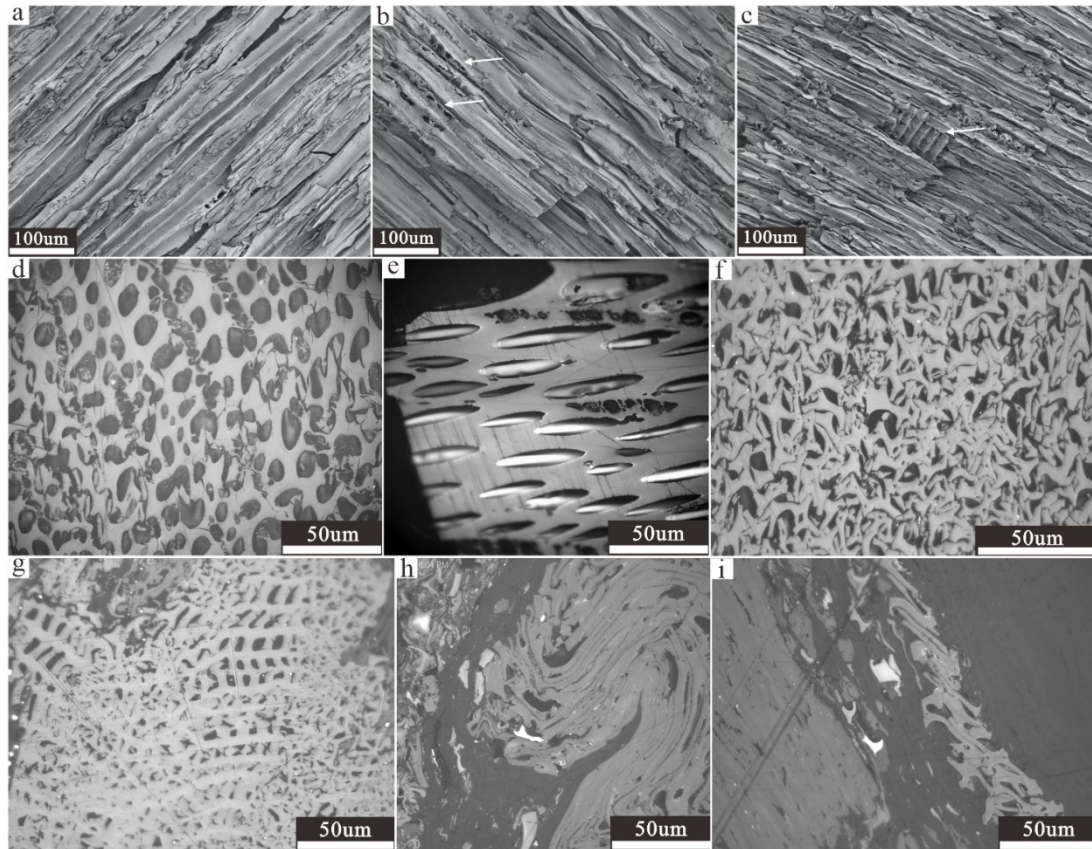


Fig. 7. Scanning electron micrographs and photomicrographs of inertinite in coal from well and outcrops in the Middle Jurassic, northwestern China. a. Longitudinal section of tracheids broken by compaction. b. Tangential section exhibiting a ray with pronounced triangular intercellular spaces between ray cells and tracheids. c. Cross section of ray cells. d-e. Cross and oblique sections of fusinite showing cell walls and ray cells. f. Inertinite with ‘bogen’ structure. g. Inertinite with regular and complete arrangement of cellular structure. h-i. Semifusinite with significantly higher reflectance than companion vitrinite. a, d, e from 8# coal seam, Yibei No. 2 open-pit coal mine. Other from 4# coal seam, Liangshuijing coal mine, Ordos Basin. d-i under reflected light.



Fig. 8. Photographs of macroscopic charcoal and plant fossils from well and outcrops in the Middle Jurassic, northwestern China. a. coal samples enriched with fusinite

from the 4# coal seam, Liangshuijing coal mine, Ordos Basin. b. fusainized coal seam with needle-like debris, SM-1 well, 578.8 m, Tuha Basin. c–e. Abundant charred plant fossil fragments in the roof and floor of 8# coal seam, Yibei No. 2 open-pit coal mine, Yili Basin. f. Lacustrine mudstone with abundant charred plant fossil fragments, Tqc-1 well, 710.9 m, Santanghu Basin. g–h. Grey sandstone with fossil fragments, from 778.2 m in the M-205 well, Santanghu Basin.

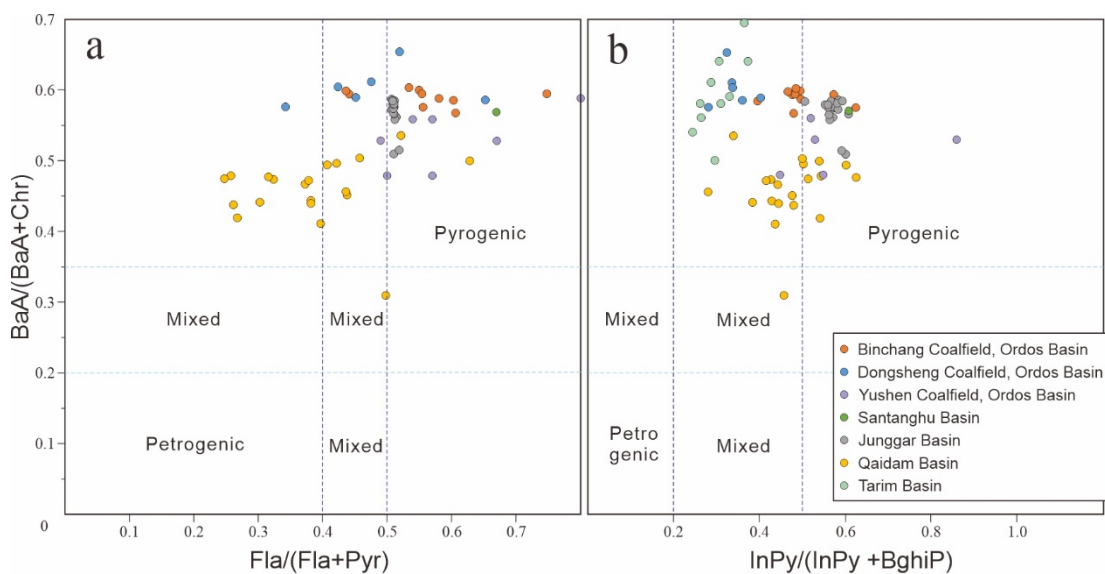


Fig. 9. Diagnostic plots indicating the origin of PAHs. a. $BaA / (BaA + Chr)$ vs. $Fla / (Fla + Pyr)$. b. $BaA / (BaA + Chr)$ vs. $InPy / (InPy + BghiP)$ (Yunker et al., 2012).

Abbreviations: Fla - Fluoranthene; Pyr - Pyrene; BaA - Benzo[a]anthracene; Chr - Chrysene; InPy - Indeno(1,2,3-*cd*) pyrene; BghiP - Benzo (g, h, i) perylene.

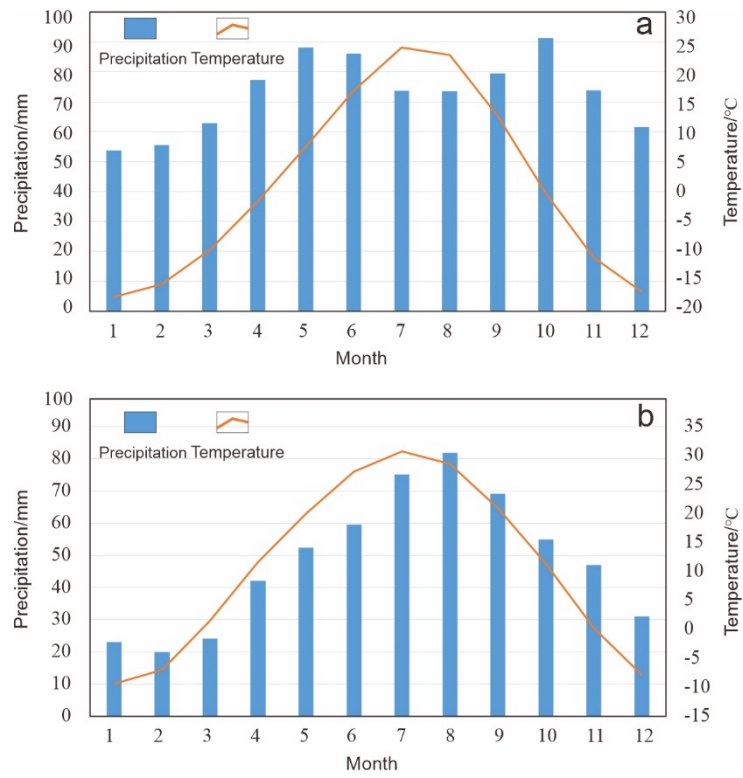


Fig. 10. Charts of monthly statistical precipitation and temperature (data from [Li et al. \(2022\)](#)). a. Early Jurassic (190 Ma); b. Middle Jurassic (170 Ma).

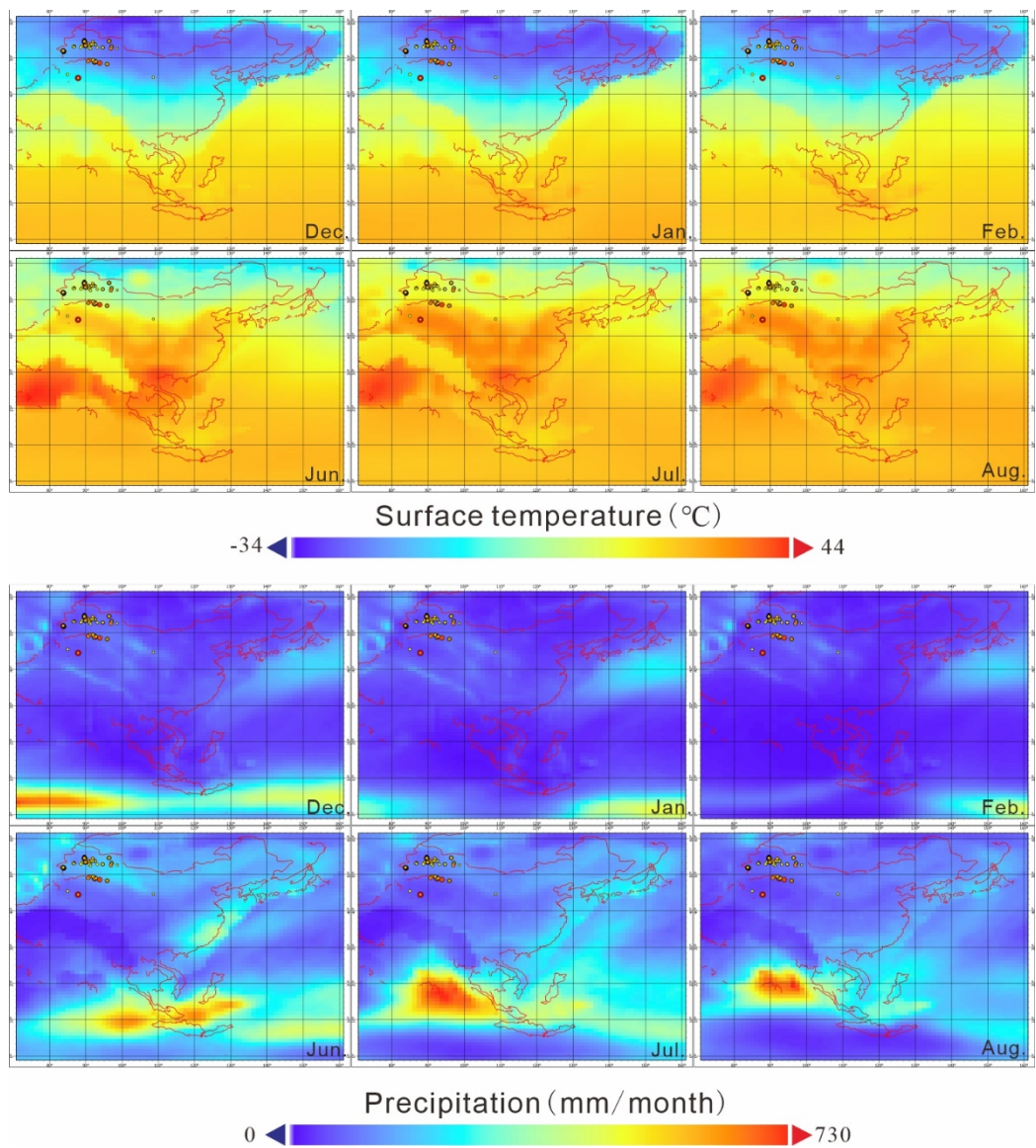


Fig. 11. Simulated Early Jurassic (190 Ma) monthly mean surface temperatures and mean precipitation (simulated data from [Li et al. \(2022\)](#)).

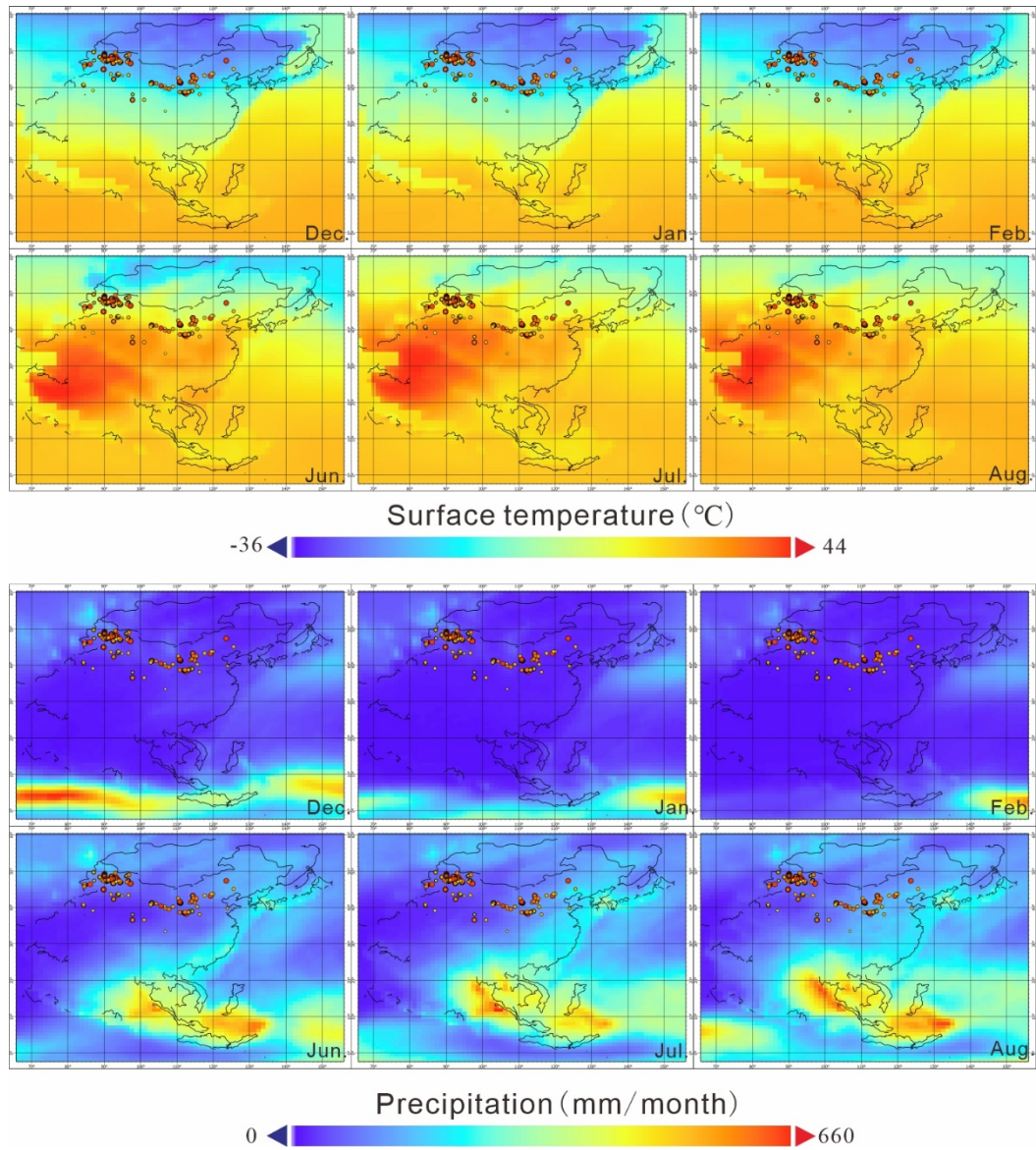


Fig. 12. Simulated Middle Jurassic (170 Ma) monthly mean surface temperatures and mean precipitation (simulated data from [Li et al. \(2022\)](#)).

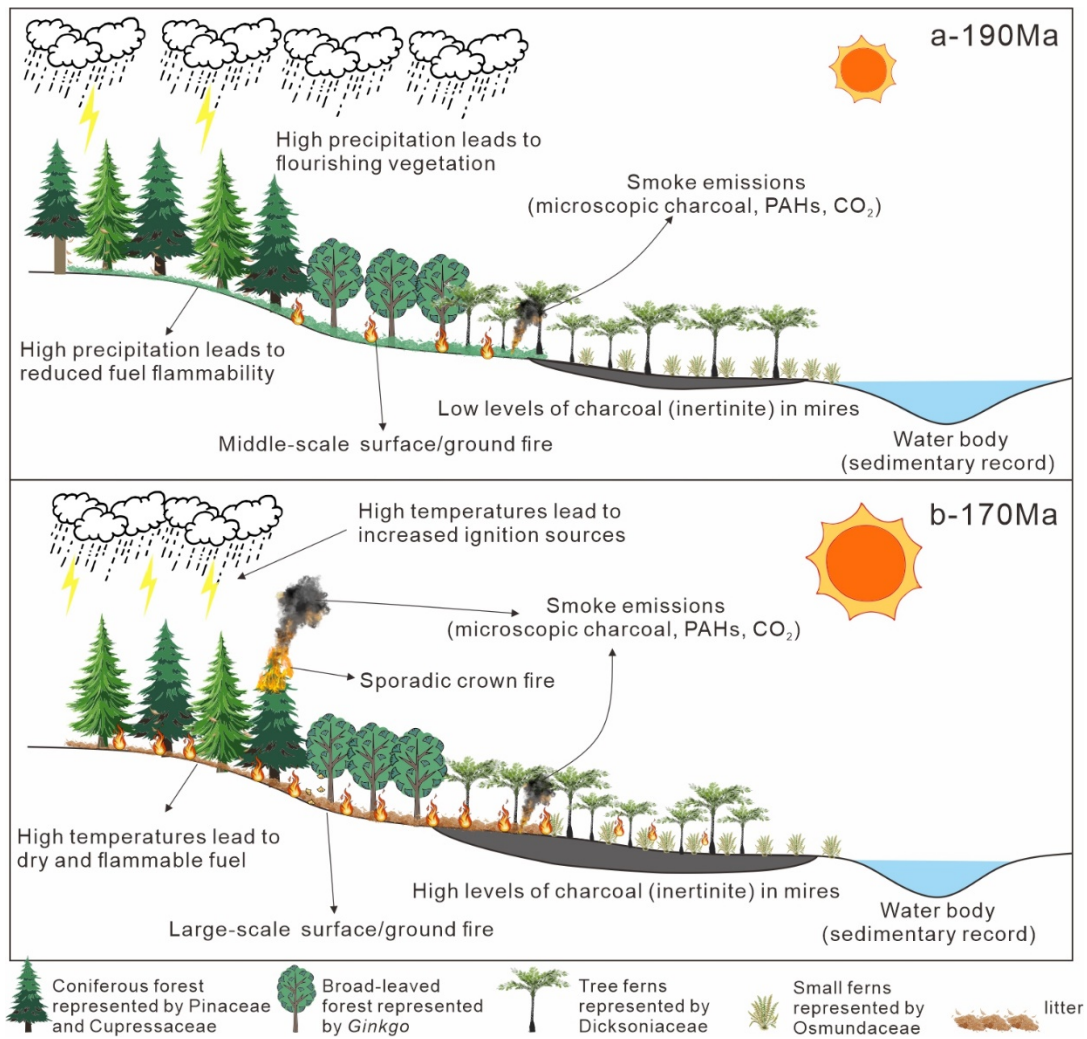


Fig. 13. Genesis pattern of inertinite-rich coals in northern China. a. Phases of low seasonal contrast (nearly Mediterranean climate). b. Phases of high seasonal contrast (nearly monsoonal climate).